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Research Proposal to the National Science Foundation  
Research Applied to National Needs (RANN)  
Advanced Energy Research and Technology

by

University of Hawaii  
Honolulu, Hawaii 96822

HAWAII GEOTHERMAL PROJECT - PHASE II  
PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION  
Amount Requested: \$1,986,513  
Proposed Duration: Twelve Months  
Requested Starting Date: January 1, 1975

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# HAWAII GEOTHERMAL PROJECT

## PHASE II

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## HAWAII GEOTHERMAL PROJECT PHASE II

### ABSTRACT OF PROPOSAL

The Hawaii Geothermal Project was established to focus the resources of the State and the University of Hawaii on a coordinated research effort leading to the development of geothermal power on the Big Island of Hawaii.

Phase I of the Project was initiated in the summer of 1973 with a \$252,000 grant from NSF-RANN, supplemented by \$100,000 each from the State and the County of Hawaii. This \$452,000 budget was organized into a multidisciplinary research effort in the following program areas: (1) Geophysical - exploratory surveys to define the most favorable areas for geothermal investigations; (2) Engineering - analytical models to assist in interpretation of geophysical results, and studies on energy recovery from hot brine; and (3) Socioeconomic - legal and regulatory aspects of ownership and administration of geothermal resources, and economic planning studies on the impact of geothermal power.

An additional \$340,000 grant was received for operational support for the Project through calendar year 1974. These funds are being used: (1) to complete the exploratory surveys and support programs in Phase I; (2) to begin the establishment of environmental baselines; and (3) to initiate planning for Phase II -- the research drilling program.

The \$1,986,513 requested in this proposal for Phase II will provide continuing operational support during calendar year 1975 for the Geophysical, Engineering, and Environmental-Socioeconomic Programs, as well as launch the exploratory Research Drilling Program. At each potential geothermal area, it is the intent to drill a number of shallow holes, a smaller number of holes to a depth of 2,000 feet or so, and one deep hole to around 6,000 feet.

The Hawaii Geothermal Project has the interest and support of both State and County governments, the business community, the utilities, and appropriate public interest groups. The potential is excellent that this significant research project involving education, private interests, and all levels of government will contribute to the technology base for exploiting geothermal energy, as well as develop a low-polluting power source to help Hawaii and the nation approach energy self-sufficiency.

## HAWAII GEOTHERMAL PROJECT

### PHASE II

#### NATIONAL AND SOCIETAL NEED

##### A. Introduction

The recent energy crisis precipitated by the embargo on Middle East oil, although global in scope, also brought into sharp focus the inadequacy of our national energy program. Both the popular and technical press have provided exhaustive information and speculation on contributing factors, the social and economic impacts, and probable duration of the shortage. Consequently, no effort will be directed in this proposal to document and analyze these various trends -- although acknowledgement is made of the fact that a global energy shortage does exist and probably will continue, in varying degrees, to the end of this century.

"Project Independence" was first enunciated by President Nixon in November 1973 and modified in January 1974 as follows: "If successful, Project Independence would by 1980 take us to a point where we are no longer dependent to any significant extent upon potentially insecure foreign supplies of energy."

A national energy self-sufficiency philosophy has particular relevance to this island State. Hawaii, which geographically consists of an island chain stretching across 350 miles of the Central Pacific and separated from the mainland United States by over 2,000 miles of that same ocean, is totally dependent for energy on seaborne petroleum. Hawaii has no known fossil fuel reserves; there is no coal coming into the State by rail; no natural gas by pipeline; and no regional electric grid to interconnect its electrical systems with those of other states or even with its separate islands. This complete lack of flexibility makes Hawaii particularly vul-

nerable to dislocations in the global energy market. This is a travesty, since the State is generously endowed with a variety and abundance of natural energy resources: geothermal, solar radiation, ocean temperature differential, wind, waves, and ocean currents -- all potential non-polluting power sources.

The candidate from among these natural energy sources which shows the highest promise for early power generation at commercial levels is geothermal energy. In Hawaii there is a variety of subsurface heat anomalies which may exist as: (1) molten magma, (2) hot rock, (3) geothermal steam, and (4) hot water. Any or all of these sources may occur in the proximity of 40°F deep-ocean water, adding to the flexibility in designing effective energy systems. The Hawaii Geothermal Project was established to investigate the potential of these geothermal resources as viable power systems for Hawaii.

#### B. Relation Of Research To Societal Problems

One positive aspect of the current energy crisis is that it has stimulated research on alternate energy systems to substitute for existing fossil fuels and nuclear fission reactors. Both of these fuel sources have serious polluting effects in addition to waste heat -- fossil fuels with their combustion by-products and fission reactors with long-lived radioactive wastes. The research results from the Hawaii Geothermal Project will contribute to better understanding of one of the natural energy resources -- geothermal energy.

There is concern that technology will be so successful in responding to the energy crisis with short-term solutions for increasing the supply and the utilization of coal, petroleum, and nuclear fission materials, that the thrust will be blunted for a long-range development of renewable natural energy sources and fusion reactors, which create only negligible amounts of radioactive wastes. As new oil fields are identified and exploited, both on and off shore; as coal liquefaction and gasification processes are developed;

and as breeder reactors increase the power generating capacity of uranium, the impetus for developing new energy systems may be lost. And this would be most short-sighted, for even if there were unlimited quantities of fossil fuels and uranium, it would be impossible to meet the ever climbing global energy requirements with these resources alone, without serious environmental degradation.

Although it is inevitable that there will be a greatly expanded usage of these polluting energy sources over the next two decades -- and, given the social and economic alternatives, this expansion seems necessary -- concerted efforts should be directed to assure that technology moves as rapidly as possible through this fossil fuel and fission era into renewable natural energy systems and fusion. This is essential both to minimize the short and long-term degradation of the environment, and to preserve for future generations the greater potential utility of fossil fuels to the petro-chemical industry and as protein for an expanding world's population.

One objective of the HGP is to establish a National Geothermal Energy Laboratory in Hawaii. The concept of this Laboratory encompasses advantages over and above the technological and scientific studies related to exploiting subsurface heat. In an environmental-socioeconomic sense, Hawaii is also a unique place to experiment and confirm modeling criteria. Here is found a virtually closed ecosystem with the environment essentially unaffected by continent-ocean interface problems, or variations caused by other population centers. Here, some 800,000 people are collected on the five major islands of an archipelago and separated both from their neighbor islands and from the mainland United States by the deep Central Pacific.

More than 80% of this population lives in Honolulu, on the island of Oahu. Thus, both the problems of a rural society and a highly-developed urban center are present, but the boundary conditions are sufficiently well defined

to lend a measure of control to this study. To complicate matters, but broaden the study base, the most obvious geothermal resources are located on the island of Hawaii, separated by some 200 miles of ocean from Oahu. Thus, a corollary to the research effort for producing power from Hawaii's heat resources is a study of the ocean transmission of that power. An additional motivation to the State is to develop an economically competitive source of energy, since the absence of fossil fuels, coupled with a widely dispersed population, causes power rates for single-family dwellings in Hawaii to be among the highest in the nation.

### C. Target Groups For Research

The primary society to be affected by this study will be the citizens of Hawaii. This primary target group includes nearly 800,000 people, living in essentially a closed ecosystem, somewhat isolated from the mainland states by over 2,000 miles of ocean. When Captain Cook discovered the Sandwich Islands, the approximately 300,000 Hawaiians were burning kukui nuts for light. Successive generations of malihinis (strangers) have been frustrated in developing the power to meet requirements imposed by their brand of civilization. They found no fossil fuels, and the short and mostly ephemeral streams offer little hydropower potential. In later years, they developed supplemental power from boilers fired with cane waste, but this provides only limited capacity. This has left imported fossil fuel as the primary energy source, since the available nuclear power plants are apparently too large to impose on the existing electrical systems, and LPG becomes quite expensive when shipped long distances in American "bottoms" as required by the Jones Act.

A secondary target group will be the people of the United States, since this research program should make a contribution to the national self-sufficiency policy. A third beneficiary will be the developing countries throughout the world, with whom Hawaii shares many power generation and distri-



bution problems. Other than the island of Oahu on which the City of Honolulu is located, there is a relatively low population density and limited industrialization. On these outer islands massive power stations with extensive distribution systems are inefficient for meeting widely dispersed low-density energy requirements, so that small generating units operating almost exclusively on petroleum provide much of the power. The technology developed by the HGP for locating, generating, and distributing geothermal energy should have application to those countries throughout the world with subsurface heat anomalies.

#### D. Consequences Of Research

The expansion of the science and technology base for the extraction of power from subsurface heat, resulting from the research projects conducted by HGP personnel, will represent a major contribution to the national quest for developing low-pollution energy sources. The variety, the availability, and the relatively well-controlled characteristics of the subsurface heat anomalies encountered on the Big Island make this a most appropriate location in which to investigate and to develop improved methods for the utilization of different forms of geothermal energy. This is another justification for locating a National Geothermal Energy Laboratory in Hawaii.

The environmental-socioeconomic aspects of this study, using the State and the Big Island as models, will also provide insight into these factors at the national level. However, the most direct and immediate beneficiaries of this program will be the State and the island of Hawaii. Power rates in Hawaii are "pegged" to oil costs. The U.S. oil quota system and the environmental mandate to use low-sulfur fuel have contributed to the relatively high cost of electricity on Oahu, where most of the population of the State is concentrated. The smaller inefficient diesel generating units and the longer

transmission distances on the sparsely populated neighbor islands run the electricity rates up even higher.

A reliable inexpensive power source would open up a variety of industrial alternatives to the people of Hawaii. One objective of the Socioeconomic Program is to investigate the feasibility of some of these alternatives, such as: (1) refining manganese nodules, which abound in the Central Pacific; (2) developing a pulp industry from sugar cane waste (bagasse); and (3) expanding agricultural and aquacultural production.

In addition to the probable economic advantage, the development of low-pollution geothermal energy would enable Hawaii to make progress toward realizing a State policy decision to promote population dispersion throughout the islands -- a policy whose implementation would be of national importance as a pattern to other states. A strong power base on each of the islands would permit such innovations as the introduction of alternative transportation systems, including electric automobiles and mass transit systems, and contribute to the preservation and enhancement of the environment in Hawaii.

#### E. Interest Of Potential Users

Hawaii has had an impressive record in both the public and the private sectors for promoting the development of new sources of energy which would lessen the import costs and environmental impact of conventional energy producing systems. Hawaiian Electric Company has financed studies on the feasibility of nuclear power systems, the development of power transmission between the islands, the application of the electric automobile toward the solution of air pollution and transportation problems, and the use of deep saline wells to limit ocean discharge of waste heat. On March 1, 1972 Lewis Lengnick, at that time President of Hawaiian Electric Company, officially announced a policy in which the company would purchase geothermal fluid, should such become avail-

HAWAIIAN ELECTRIC COMPANY, INC.

Box 2750 / Honolulu, Hawaii / 96803

CARL H. WILLIAMS  
PRESIDENT

June 18, 1974

Dr. John W. Shupe  
Dean of Engineering  
University of Hawaii  
Honolulu, Hawaii 96822

Dear John:

Through my participation on the Advisory Committee to the Hawaii Geothermal Project and through Francis Montgomery's (Vice President, Engineering) attendance at the National Liaison Board meeting in February 1974, we have had the opportunity to follow the development of this geothermal project since the initial meeting of scientists held at the Geothermal Symposium in 1972.

We at Hawaiian Electric Company continue to be very interested in this development and wish to continue to participate in the project as we have in the past. As we stated in our letter to you of March 1972, it is not feasible for a power company to supply venture capital for the search of geothermal fluid in Hawaii. However, we continue to be interested in the purchase of geothermal fluid which may be developed, provided an adequate amount of suitable quality can be developed at an economical cost to us. A power company's commitment for such would facilitate obtaining venture capital from others.

Hawaiian Electric Company is actively investigating alternate sources of power at the present time that either reduce pollution, reduce our dependence on fossil fuel, or reduce costs. It appears to us that geothermal power offers some relief in the reduction of pollution, reduction of dependence on fossil fuels, and reduction in costs, and I would like to go on record as stating that Hawaiian Electric Company, including its wholly owned subsidiary, Hilo Electric Light Company, will continue to work with any organization that is searching for geothermal fluid and that we will enter into a contract to purchase such geothermal fluid if an adequate supply of suitable quality is developed at an economical cost to us.

The quality, quantity and cost of geothermal fluid are matters too broad to be covered in a letter of intent of this type, but our engineering and operating personnel will continue to be available to discuss these in greater detail with you as the project progresses.

Very truly yours,



Copies to: Acting Governor George R. Ariyoshi  
Mayor Frank Fasi  
Mayor Bruce McCall  
David C. McClung, President of the Senate  
Tadao Beppu, Speaker of the House

able in sufficient quality and quantity to make it economically feasible for power generation. This policy was reiterated recently by Carl Williams, current President of Hawaiian Electric Company and member of the Hawaii Advisory Committee to the HGP. (Refer to attached copy of Mr. Williams' letter.)

In the early 1960's, drillings were made in the Puna Rift area of the island of Hawaii for the specific purpose of locating sites where geothermal steam from water intrusion might be used for power generation. The results were non-conclusive, and the project was abandoned before any deep drilling was accomplished. This had a negative effect on further geothermal developments, but in recent years the interest has surfaced again.

Seed money and/or encouragement to look into the feasibility of new energy systems has come from a variety of sources: (1) the 1970 State Legislature passed a resolution (no funds) requesting the University of Hawaii to initiate studies on new sources of energy; (2) in 1971 the State and County of Hawaii provided \$10,000 to the University for an energy-aquaculture study; (3) a small grant (\$5,000) from the Atomic Energy Commission aided the assessment of the geothermal potential of this island chain; (4) the Hawaiian Electric Company provided initially \$3,000 and later an additional \$9,000 to assist with various phases of the HGP; and (5) the Sandia Corporation contributed \$12,000 to look into some of the properties of molten magma. More substantive funding has come from the Hawaii State Legislature: (1) \$200,000 in 1972 -- \$100,000 of which was administered through the County of Hawaii budget; and (2) \$500,000 approved in the 1974 Capital Improvements Budget for exploratory geothermal drilling, contingent upon federal matching.

Local interest in the HGP has been high. Encouragement, endorsement, assistance, and/or interaction has taken place with the following organizations:

### State Departments and Offices

Department of Planning and Economic Development  
Department of Land and Natural Resources  
Department of the Attorney General  
Office of Science Policy  
Office of Marine Affairs  
Office of Environmental Quality Control  
State Task Force on Energy Policy

### County of Hawaii

The Mayor's Office  
Department of Research and Development  
Hawaii County Council

### Electric Utilities

Hawaiian Electric Company  
Hilo Electric Light Company

### Business and Industrial Concerns

Bishop Estate  
Campbell Estate  
C. Brewer and Company, Ltd.  
Pacific Resources, Inc.  
Water Resources International  
Honolulu Chamber of Commerce  
Hilo Chamber of Commerce

In addition, representatives from environmental and citizen groups are included in the Hawaii Advisory Committee, as described under the Management Program. Interaction with other geothermal projects is maintained through the National Liaison Board, also discussed in the Management Program, and through other professional contacts.

The ground work has been laid and a favorable combination of circumstances exists for involving education, private interests, and government at the local, state and federal levels in this significant research project for expanding the technology base on geothermal energy and for developing a low-pollution power source for Hawaii and the nation. During both the 1972 and

1973 Sessions, Congressman Spark M. Matsunaga of Hawaii introduced bills " -- to promote the exploration and development of geothermal resources through cooperation between the Federal Government and private enterprise." Included in these bills was provision for the establishment of a Geothermal Research Institute in Hawaii. HGP objectives are consistent with Mr. Matsunaga's imaginative proposal.

#### F. Policy Issues And Decisions

Policy issues related to this proposal involve state and local governmental practices on land use, mineral rights, and ownership of geothermal resources. The impact which the HGP has had to date in this area is reflected in part by the passage of House Bill 2197-74, A Bill Relating to Reservation and Disposition of Government Mineral Rights, as discussed in the Environmental-Socioeconomic Program. Additional input will be provided in establishing appropriate state regulatory practices for the exploitation of geothermal resources.

Engineering and environmental studies to be conducted by HGP personnel will establish environmental baselines and criteria to serve as the foundation upon which Environmental Impact Statements will be prepared -- for both the exploratory and the commercial drilling program.

Economic and planning studies included in this program will investigate alternatives for orderly growth of new industries and population centers which may result from the probable introduction of a new and economically competitive power source for Hawaii. The need for clear policies and laws is evident; appropriate controls and incentives must be established in order to encourage the investment of private capital in the development and distribution of power, while at the same time minimizing the environmental and social degradation which could result from unregulated "gold rush" speculation and exploitation of the resource.

## HAWAII GEOTHERMAL PROJECT

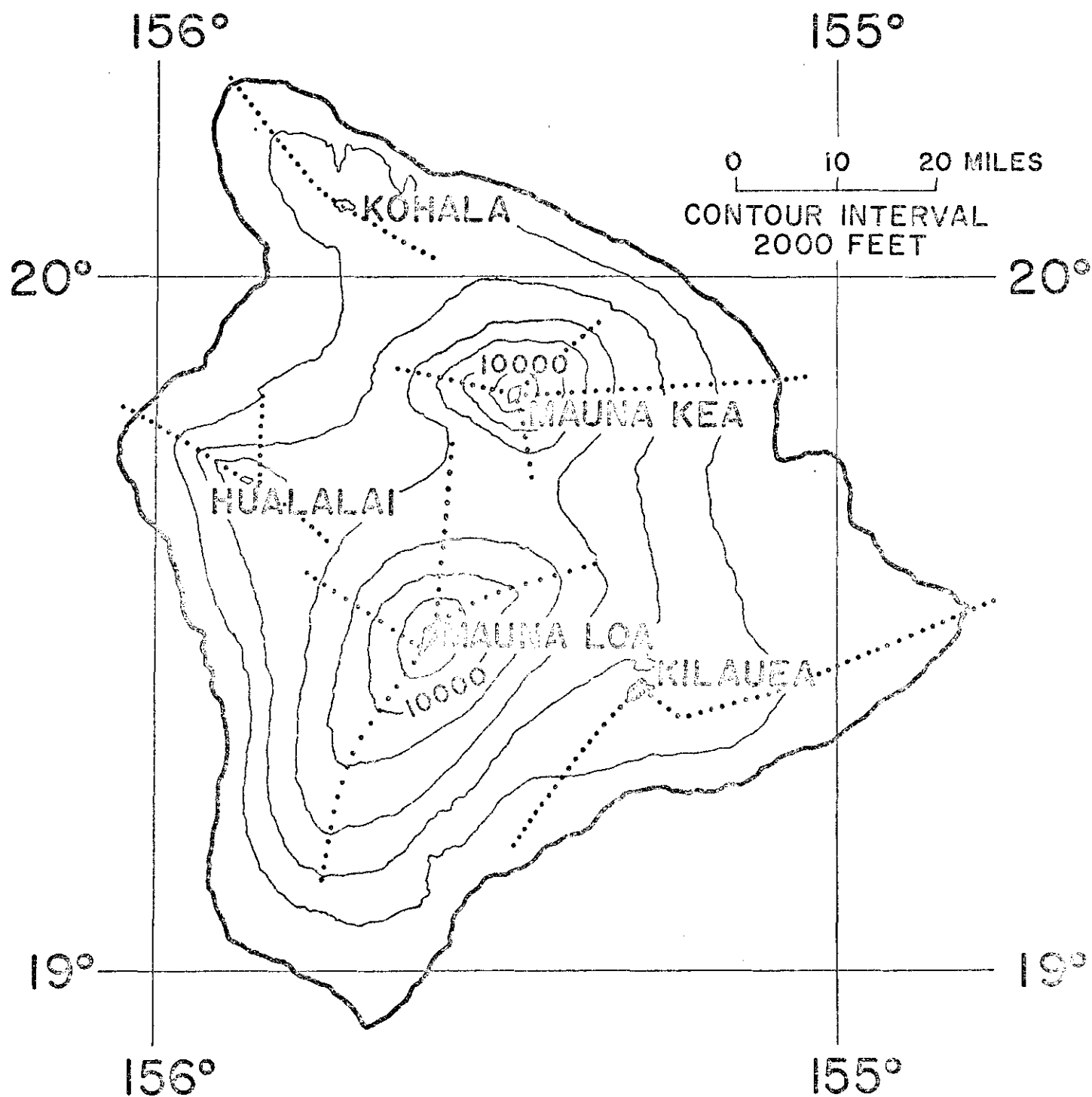
### PHASE II

#### OVERVIEW OF PHASES I AND II OF THE HGP

The Hawaii Geothermal Project (HGP) was organized to focus the resources of the University, the State, and the County of Hawaii on the identification, generation, and utilization of geothermal energy on the Big Island of Hawaii. Figure 1 shows the five volcanoes which form this largest island in the Hawaiian chain. Hawaii is also the youngest of the islands and is still experiencing growth from recent activity of the Mauna Loa and Kilauea volcanoes. Consequently, the Big Island was selected as the obvious site for initial geothermal exploration, but subsequent surveys will proceed up the island chain.

The research program as developed by the HGP involves an interdisciplinary team of researchers from throughout the University system, which conduct scientific investigations on both short-range exploratory and applied technology tasks to assist in the early development of any conventional geothermal resource -- steam or hot water -- that may exist on the Big Island, as well as long-range research studies of a more basic nature. The overall goals and objectives of the HGP, many of which will contribute to the technology base for the recovery of energy from subsurface heat, no matter where it occurs, include:

1. Improvement of geophysical survey techniques for locating underground heat resources.
2. Identification of potential geothermal resources, initially on the Big Island, but ultimately for the entire island chain.
3. Experimentation with deep-drilling techniques for subsurface heat.
4. Development of efficient, environmentally clean systems for conversion of underground heat resources to useful energy.



## VOLCANOES & RIFT ZONES ON THE ISLAND OF HAWAII

Figure I



5. Completion of socioeconomic and legal studies for conversion of underground heat resources to useful energy.
6. Establishment of environmental base lines with which to monitor subsequent geothermal development.
7. Development of a geothermal production field and prototype power plant on the Big Island, which will serve as a National Geothermal Energy Laboratory on technological developments in power production and reservoir management of earth heat resources.

The HGP came into being when the 1972 Hawaii State Legislature allocated \$200,000 for geothermal research -- \$100,000 to be administered through the County of Hawaii budget. This action was taken prior to the energy crisis and was a progressive step for a state governing body to take. An initial grant of \$252,000 was received from the Research Applied to National Needs Program of the National Science Foundation in May 1973; the State and County of Hawaii released their \$200,000 shortly afterwards; and Phase I of the HGP got underway during the summer of 1973.

Research for Phase I was organized into three separate programs, with the initial \$452,000 budget supporting the following activity:

Geophysical Program -- Augustine S. Furumoto, Director

- Photogeologic (Infrared Scanning) Survey
- Electromagnetic Survey
- Electrical Resistivity Survey
- Microearthquake and Microseismic Surveys

Engineering Program -- Paul C. Yuen, Director

- Well Test Analysis
- Ghyben-Herzberg Lens Dynamics
- Energy Extraction from Hot Brine

Environmental-Socioeconomic Program -- Robert M. Kamins, Director

- Land Use, Regulations and Planning
- Economic Analysis

The major emphasis of Phase I has been on the Geophysical Program, since the issue of if and where geothermal resources exist is crucial to the Project. However, parallel engineering studies were initiated to investigate problems involving reservoir characteristics and plant design, and legal studies were begun to help clarify regulatory and ownership rights -- since these points must be resolved before any investment capital can be identified for geothermal development in Hawaii. Good progress has been made to date in all three programs and is summarized in subsequent sections of this proposal.

It was impossible to complete the geophysical surveys and to analyze all of the data associated with the field studies during the first year of the Project. Therefore, a proposal for a continuation grant of \$340,000 was made to the National Science Foundation to provide operating support for the Phase I research program through calendar year 1974. This proposal was funded by the Foundation, and currently the HGP is fully mobilized to complete this phase of the study. The geophysical surveys to date have been primarily reconnaissance surveys to identify general areas of potential interest. The remainder of 1974 will be devoted to refining the preliminary geophysical results and, to assist in this endeavor, a new task on Geochemical Surveys has been added. Parallel studies will continue in the Engineering and Socio-economic Programs, with preliminary work beginning on establishing environmental baselines to assist in monitoring subsequent drilling operations.

On the basis of preliminary results from Phase I, in conjunction with surveys and studies conducted on the Big Island by a variety of scientific disciplines over the past several decades, it has become obvious that an exploratory research drilling program is essential to establish actual identity of the subsurface conditions predicted by the surveys. The major thrust of this proposal is to initiate the drilling program as Phase II of the HGP,

in order to verify interpretation of the scientific data and to determine if conventional geothermal resources exist on Hawaii. Research activity will also continue in each of the three complementary programs: Geophysical, Engineering, Environmental-Socioeconomic.

Referring again to Figure 1, tentative plans call for initial drilling to take place in early 1975 along the Eastern Rift of Kilauea, followed by the Southwest Rifts of Kilauea and Mauna Loa. At each location the drilling program will include a number of shallow holes a few hundred feet deep, a smaller number of holes 2,000 feet or so in depth, and one deep hole that may extend to 6,000 feet. The drilling program will be under the direction of Dr. Agatin T. Abbott and the Site Selection and Operations Committee, which he established to assist with key decisions both for preliminary planning and as drilling progresses. Tentative scheduling, operation, and information to be obtained from the drilling program is discussed in detail in a subsequent section.

In summary, the overall objective of Phases I and II of the HGP is to solve the problems and to answer the questions -- geophysical, technological, legal, environmental, social, economic -- relating to the development of a conventional geothermal resource in Hawaii. If such a resource is identified, it is the intent to carry this development to the proof of concept stage, through the construction of a 5- to 10-megawatt prototype geothermal power plant. This will be done in cooperation with the local electrical utility, which is expected to finance the basic cost of the plant and include it in the electric system for the Big Island. The HGP will endeavor to identify public funding in order to: (1) make the entire operation environmentally pure, as a demonstration of the non-polluting potential of geothermal energy; and (2) instrument both the wells and the plant sufficiently so that adequate

operational data and reservoir characteristics can be obtained. This instrumented prototype power plant and geothermal field will form the nucleus for a National Geothermal Energy Laboratory to be used by engineers and scientists from throughout the world to study reservoir characteristics and evaluate performance theories.

## HAWAII GEOTHERMAL PROJECT

### PHASE II

#### MANAGEMENT PROGRAM (1.0)

##### A. The Management Plan

The Hawaii Geothermal Project involves more than forty researchers and support staff from throughout the University of Hawaii system. Both major campuses on Oahu and the Big Island are represented, along with over a dozen research institutes and academic units. Many of the State and County agencies and their staffs are directly involved in the HGP, along with numerous mainland consultants, research organizations, engineering and drilling subcontractors. This project has great potential importance, both for the University and the State, and effective coordination among the wide variety of technological, socioeconomic, and political interests at all educational, private, and governmental levels is essential. The management plan was developed with these diverse interests in mind.

Figure M-1 is an organizational chart for Phase II of the HGP. Principal Investigator and Project Director is John W. Shupe, Dean of Engineering. Dr. Shupe serves on the State Environmental Council and was recently appointed by the Governor to establish and chair a Committee on Alternate Energy Sources for Hawaii. He will devote quarter-time to coordination of the HGP.

A co-principal investigator is responsible for the planning and for the direct technical supervision in each of the four research programs: (A) Geophysical Program -- Dr. Augustine S. Furumoto, Professor of Geophysics; (B) Engineering Program -- Dr. Paul C. Yuen, Professor of Electrical Engineering; (C) Environmental-Socioeconomic Program -- Dr. Robert M. Kamins, Professor of Economics; and (D) Dr. Agatin T. Abbott, Professor and Chairman of Geology and Geophysics. Each of these program directors will devote half-time to admini-

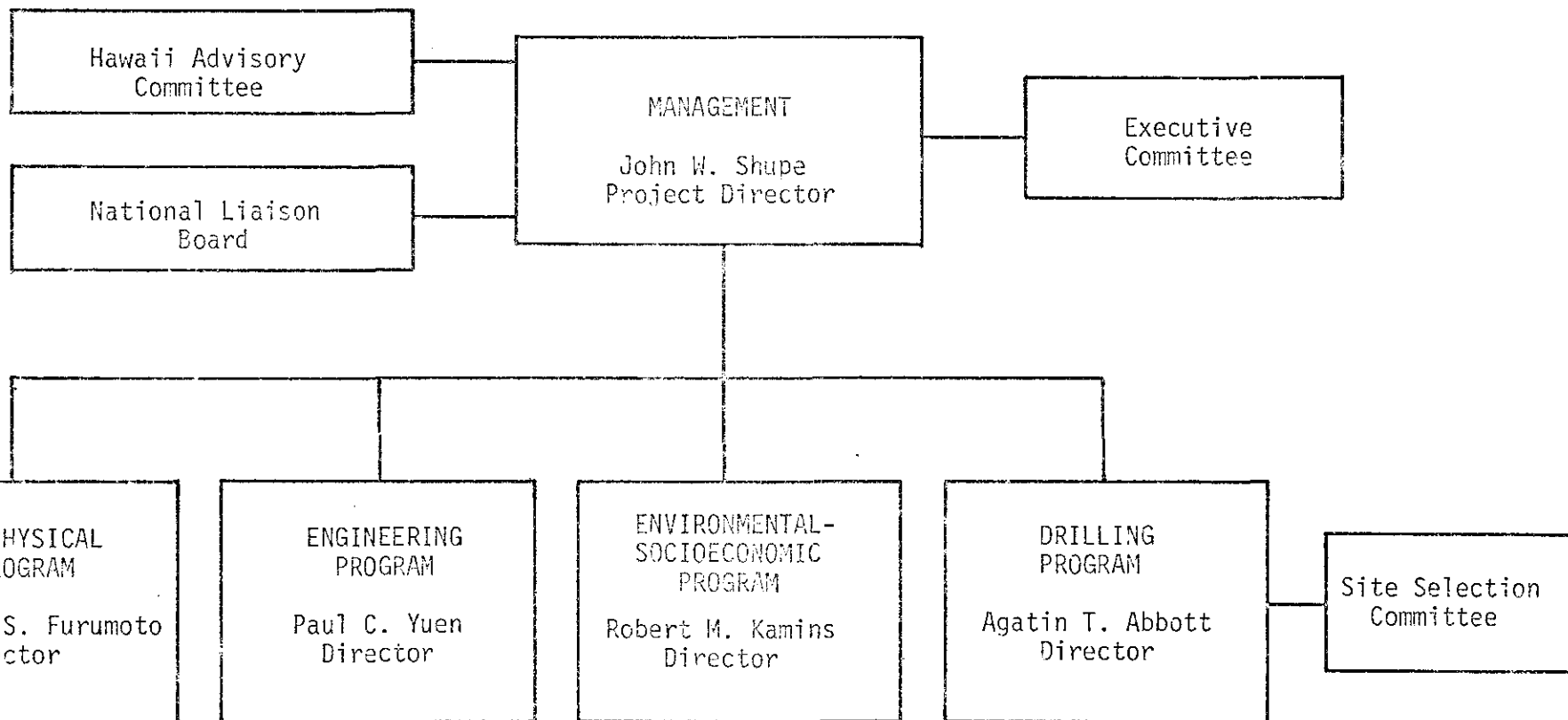


Figure M-1

ORGANIZATIONAL CHART  
HAWAII GEOTHERMAL PROJECT - PHASE II

stration, coordination, and implementation of his respective research program. Although there is a separate budget assigned to each program -- in order to assist in establishing technical and fiscal authority and accountability -- the four co-P.I.'s will meet regularly to help facilitate overall administration of the project.

The HGP Executive Committee consists of the five principal investigators, plus two additional members who will assist the Project Director in assuring the necessary visibility and support throughout the academic community, as well as by the governmental and private sectors: (1) Dr. John P. Craven, Dean of Marine Programs at the University and Director of Marine Affairs for the State of Hawaii; and (2) Dr. George P. Woollard, Director of the Hawaii Institute of Geophysics and a member of the Governor's Science and Technology Advisory Committee. The Executive Committee will: (1) provide technical input in establishing overall goals and objectives; (2) review and approve the research program developed under the leadership of the principal investigators; (3) maintain liaison essential to project support, both on and off campus; and (4) monitor progress of the project. The Project Director assumes full administrative responsibility for implementation of the HGP, and assisting with this effort is Ms. Carolyn Sharma, Administrative Assistant.

To assure that the HGP has both local and national relevance, systematic evaluation and advice will continue to be provided to the Executive Committee and the P.I.'s from numerous sources: (A) the NSF Project Manager; (B) the National Liaison Board; and (C) the Hawaii Advisory Committee. The National Liaison Board (membership list attached) consists of the project leaders of other RANN-supported geothermal programs, along with a few of the national leaders in geothermal research and development. This Liaison Board meets annually in Hawaii to review program progress, to exchange current information

HGP NATIONAL LIAISON BOARD

Mr. David N. Anderson, Geothermal Officer  
State of California Resources Agency  
Department of Conservation  
Division of Oil and Gas  
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Advanced Energy Research and Technology  
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Dr. George Kennedy  
Institute of Geophysics and  
Planetary Physics  
University of California, Los Angeles  
Los Angeles, California 90024

Dr. James T. Kuwada  
Rogers Engineering Company, Inc.  
16 Beale Street  
San Francisco, California 94105

Dr. Henry J. Ramey, Jr.  
Professor of Petroleum Engineering  
School of Earth Sciences  
Stanford University  
Stanford, California 94305

Dr. Robert W. Rex  
Republic Geothermal, Inc.  
11848 East Washington Boulevard  
Whittier, California 90606

Dr. Donald H. Stewart  
Battelle Pacific Northwest Laboratories  
Post Office Box 999  
Richland, Washington 99352

Dr. Donald E. White  
Geothermal Research Program  
U.S. Department of the Interior  
Geological Survey, Geologic Division  
345 Middlefield Road  
Menlo Park, California 94025



## HQP ADVISORY COMMITTEE

Ms. Sophie Ann Aoki  
Life of the Land (Environmental Program)  
404 Piikoi Street, Suite 209  
Honolulu, Hawaii 96814

Mr. James Bacon, Executive Director  
Congress of the Hawaiian People  
Suite 351, Alexander Young Building  
Honolulu, Hawaii 96813

Dr. John P. Craven, Dean  
Marine Programs  
University of Hawaii  
Holmes Hall 401  
Honolulu, Hawaii 96822

Mr. Robert F. Ellis, President  
Chamber of Commerce of Hawaii  
Dillingham Transportation Building  
Honolulu, Hawaii 96813

Mr. Robert H. Hughes  
Senior Vice President  
C. Brewer and Company, Ltd.  
Post Office Box 3470  
Honolulu, Hawaii 96801

Mr. Sunao Kido, Chairman of the Board  
Department of Land and Natural Resources  
State of Hawaii  
Post Office Box 621  
Honolulu, Hawaii 96809

Mayor Shunichi Kimura  
County of Hawaii  
25 Aupuni Street  
Hilo, Hawaii 96720

Dr. Shelley M. Mark, Director  
Department of Planning and  
Economic Development  
State of Hawaii  
Post Office Box 2359  
Honolulu, Hawaii 96804

Dr. Richard Marland, Director  
Governor's Office of Environmental  
Quality Control  
550 Halekauwila Street, Third Floor  
Honolulu, Hawaii 96813

Dr. Fujio Matsuda, Vice President  
Business Affairs  
University of Hawaii  
Bachman Hall 211  
Honolulu, Hawaii 96822

Dr. Howard P. McKaughan  
Director of Research  
University of Hawaii  
Spalding Hall 360  
Honolulu, Hawaii 96822

Dr. Paul M. Miwa, Chancellor  
University of Hawaii - Hilo Campus  
1643 Kilauea Avenue  
Hilo, Hawaii, 96720

Dr. Donald W. Peterson  
Scientist-in-Charge  
U.S. Department of the Interior  
Geological Survey  
Hawaiian Volcano Observatory  
Hawaii National Park, Hawaii 96718

Mr. Herbert M. Richards, Jr.  
Vice Chairman, Board of Regents  
University of Hawaii  
Box 837  
Kamuela, Hawaii 96743

Mr. Carl H. Williams, President  
Hawaiian Electric Company  
Post Office Box 2750  
Honolulu, Hawaii 96803

Dr. George P. Woollard, Director  
Hawaii Institute of Geophysics  
University of Hawaii, HIG 131  
Honolulu, Hawaii 96822

on geothermal science and technology, and to advise on future planning and implementation for the HGP.

The Hawaii Advisory Committee (membership list attached) was established to provide interaction with key individuals from industry, government, and the scientific community, whose support is essential to the introduction of geothermal power in Hawaii. Serving on this committee are the Directors of the State Office of Environmental Quality Control and the Department of Planning and Economic Development; the president of the major electric utility company; Director of the County of Hawaii Office of Research and Development; a cross-section of business and industrial leaders of the community; and representatives of citizen groups. This committee meets semi-annually and supplements the Executive Committee in providing the necessary visibility for the HGP, both on and off campus, to assure public and private support for geothermal power in Hawaii.

The composition and function of the Site Selection and Operations Committee is discussed in the Drilling Program.

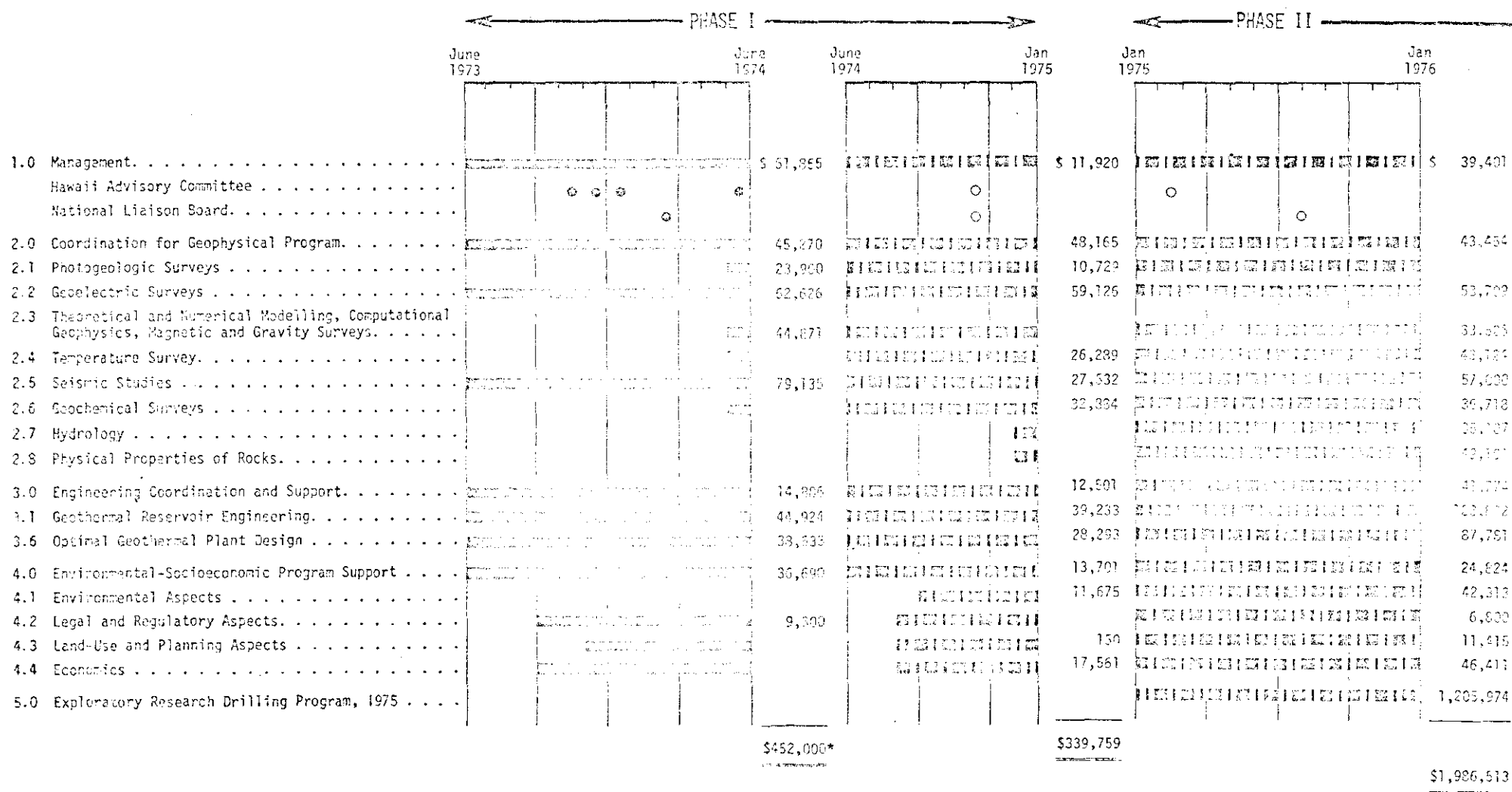
The legal fiscal agent for the program will be the Office of Research Administration of the University of Hawaii. The Foundation has engaged in many previous contracts through this agency of the University, so a backlog of experience in administering Foundation contracts and grants already exists.

#### B. Program Planning And Expenditure Schedule

Figure M-II lists the program and expenditure schedule for each research task throughout both Phases I and II. This one table summarizes the level of activity during each funding period for all of the research tasks, so provides a general overview of funding and program activity up to this date, as well as for Phase II support requested in this proposal.

The three separate sections reflect the research programs during each

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(\*Includes \$100,000 from State of Hawaii and \$100,000 from County of Hawaii)

FIGURE M-II  
HAWAII GEOTHERMAL PROJECT  
PROGRAM PLANNING AND EXPENDITURE SCHEDULE

funding period: (1) June 1, 1973 through May 31, 1974 -- \$452,000, with \$252,000 from NSF and \$200,000 from the State and County of Hawaii; (2) June 1, 1974 through December 31, 1974 -- \$340,000 from NSF, of which \$216,000 has been allocated from FY 1974 and the remaining \$124,000 committed from FY 1975; and (3) January 1, 1975 through December 31, 1975 -- \$1,986,513 requested from NSF in this proposal.

### C. HGP Personnel Summary

#### Executive Committee

Agatin T. Abbott, Professor and Chairman of Geology and Geophysics  
John P. Craven, Dean of Marine Programs  
Augustine S. Furumoto, Professor of Geophysics  
Robert M. Kamins, Professor of Economics  
John W. Shupe, Dean of Engineering  
George P. Woollard, Director of Hawaii Institute of Geophysics  
Paul C. Yuen, Associate Dean of Engineering

#### Geophysical Program

Robert W. Buddemeier, Associate Professor of Chemistry  
Pow-Foong Fan, Associate Professor of Geology  
Augustine S. Furumoto, Professor of Geophysics  
Robert Harvey, Research Associate  
Douglas P. Klein, Research Associate  
Peter M. Kroopnick, Assistant Professor of Oceanography  
L. Stephen Lau, Director of Water Resources Research Center  
Murli H. Manghnani, Professor of Geophysics  
Roger A. Norris, Research Associate  
Ramanan Ramanantoandro, Assistant Geophysicist

#### Engineering Program

Hi Chang Chai, Professor and Chairman of Mechanical Engineering  
Bill H. Chen, Assistant Professor of Engineering (Hilo Campus)  
Ping Cheng, Professor of Mechanical Engineering  
James C. S. Chou, Professor of Mechanical Engineering

Deane H. Kihara, Associate Professor of Mechanical Engineering  
Kah Hie Lau, Assistant Professor of Engineering (Hilo Campus)  
L. Stephen Lau, Director of Water Resources Research Center  
Patrick K. Takahashi, Assistant Professor of Civil Engineering  
Paul C. Yuen, Associate Dean of Engineering

Environmental-Socioeconomic Program

Andrew Berger, Professor of Zoology  
Michael J. Chun, Assistant Professor of Public Health  
Doak C. Cox, Director, Environmental Center  
P. Anders Daniels, Assistant Professor of Meteorology  
Nabil A. El-Ramly, Associate Professor of Business Economics  
Ruth Gay, Instructor, Botany  
Eugene M. Grabbe, Director, State Center for Science Policy & Technology Assessment  
Jerry M. Johnson, Assistant Director of Environmental Center  
Robert M. Kamins, Professor of Economics  
James E. T. Moncur, Assistant Professor of Economics  
Richard E. Peterson, Associate Professor of Business Economics  
Kap-Kyung Seo, Professor of Business Economics  
Sanford M. Siegel, Professor of Botany

Drilling Program

Agatin T. Abbott, Professor & Chairman of Geology and Geophysics  
Gordon A. Macdonald, Senior Professor of Geology  
Donald W. Peterson, Geologist & Scientist-in-Charge, Hawaiian Volcano Observatory  
Charles J. Zablocki, Physicist, Hawaiian Volcano Observatory

Vitae and bibliographies for these participants are listed at the end of each of the program descriptions.

D. Management Program - Phase II

During Phase I of the Hawaii Geothermal Project the Management Program has provided: (1) coordination of activities among the research programs; (2) administrative services to assist with implementation of the research; and (3) promotional efforts at the University, State, and Federal levels to

help assure adequate visibility and support for the HGP.

The following organizations (all of which were discussed earlier) were established: (1) the HGP Executive Committee; (2) the Hawaii Advisory Committee; and (3) the National Liaison Board. Operational guidelines and membership lists were developed for these advisory groups, and to date three effective meetings have been held with the Advisory Group, and a most informative evaluation session with the National Liaison Board.

The level of interest in geothermal energy in Hawaii continues to run high. It has received added impetus from the recent energy crisis -- and the resulting lines at the gas pumps. This interest is reflected in continuing State support for geothermal R & D, the most recent of which is the \$500,000 allocation for exploratory geothermal drilling.

For Phase II the Management Program will continue with the same responsibilities, while endeavoring to reinforce existing interest and support for the HGP and identify new sources for potential interaction. A joint meeting of the National and Hawaii advisory groups is scheduled for November 1974, with subsequent meetings at the usual intervals throughout 1975.

Close liaison is maintained with all four congressional delegates, who are kept well informed on progress of the HGP. Excellent support, information, and advice is provided by our congressional delegates on any shifts in organizational structure and funding philosophy of federal agencies.

During Phase I, \$63,600 was assigned to the Management Program to provide support services, fund the expenses of the Hawaii Advisory Committee and the National Liaison Board, and provide a contingency fund to meet any emergencies that might arise in the research programs. Now that the Project is well established and the program expenses reasonably well defined, it is not necessary to retain a major contingency fund. Therefore, the budget for

Phase II has been reduced to \$39,400. Included in the budget renewal is provision for one meeting of the National Liaison Board in Honolulu, and two meetings of the Hawaii Advisory Committee.

VITAE AND BIBLIOGRAPHIES FOR  
MANAGEMENT PROGRAM



NAME JOHN P. CRAVEN

PRESENT POSITION Dean of Marine Programs  
Professor of Ocean Engineering

EDUCATION Ph.D., University of Iowa, 1951  
M.S., California Institute of Technology, 1947  
B.S., Cornell University, 1946

PAST EMPLOYMENT

1969-1970	Visiting Professor of Ocean Engineering and Political Science, Massachusetts Institute of Technology
1958-1970	Chief Scientist, U.S. Navy
1961-1967	Senior Hydrodynamicist, David Taylor Model Basin

PUBLICATIONS

Ocean Engineering Systems, MIT Press, 1971.

"Res Nullius De Facto" -- The limits of technology. Symposium on the  
International Regime of the Sea-Bed, Pallazzo Corsini, Rome, pp. 1-18, 1969.

"Ocean Technology and Submarine Warfare," Adelphi Papers, March 1968, No. 46.  
Institute for Strategic Studies.

"The Design of Deep Submersibles," The Society of Naval Architects & Marine  
Engineers. June 1968, No. 9.

"Engineering Problems of Ocean Systems," Ocean Engineering, Vol. 1, pp. 127-131.  
Pergamon Press. 1968.

"The Fourth Dimension of Seapower," Vol. XXII, No. 2. The JAG Journal,  
September-November 1967.

"An Assessment of the Future of Deep-Ocean Technology," Astronautics &  
Aeronautics, July 1967, pp. 36-42.

"Ocean Technology and Submarine Warfare," Institute for Strategic Studies,  
9th Annual Conference, Elsinore, Denmark, pp. 1-27, 1967.

"Technology and the Law of the Sea," Mershon Conference, Columbus, Ohio.  
pp. 1-36, 1967.

HONORS AND AWARDS

Member of National Academy of Engineering

Arthur S. Fleming Award

Parsons Award

U.S. Navy Distinguished Civilian Service Award

Department of Defense Distinguished Civilian Award

CAROLYN M. SHARMA

Administrative Assistant

EDUCATION: Dobbins Vocational Technical School, Diploma, 1958  
l'Alliance Francaise, Paris, 3rd Degree Certificate, 1963  
Sorbonne, University of Paris, 1963-1964  
University of Pennsylvania, 1966-1967  
American Buddhist Academy of New York, 1967-1968

PAST EMPLOYMENT:

1958-1959 Secretary to Director, Keystone Diamond Exchange,  
Philadelphia, Pennsylvania

1959-1960 Secretary to Director of Casework, Women's Christian  
Alliance, Philadelphia, Pennsylvania

1960-1962 Secretary to Chief of Security, General Electric Company,  
Missile and Space Vehicle Department, Valley Forge, Penna.

1962 Secretary to Base Surgeon-General, 7369th Combat Support  
Group, USAF, Phalsbourg, France

1964 Secretary to Director of Logistics, USAFE Headquarters,  
Wiesbaden, Germany

1965 Translator, Jaguar, Inc., Paris, France

1965 Interpreter, Consular Division, Embassy of India, Paris,  
France

1965-1966 Secretary to Customer Relations Director, Gulf Oil  
Company, Bala Cynwydd, Pennsylvania

1966-1967 Secretary, Intercollegiate Athletic Department, University  
of Pennsylvania, Philadelphia, Pennsylvania

1967-1968 Secretary to Publicity Director, United Jewish Appeal of  
Greater New York, New York City, New York

1968-1969 Secretary to Administrative Vice President, Trust Division,  
First Hawaiian Bank, Honolulu, Hawaii

1969-1971 Secretary to the President, Financial Security, Ltd.,  
Honolulu, Hawaii

1971-1973 Executive Secretary, Kentron Hawaii, Ltd., Honolulu, Hawaii

1973 Executive Secretary, Alfred A. Yee & Associates, Consulting  
Engineers, Honolulu, Hawaii

1973-Present Administrative Assistant, Hawaii Geothermal Project,  
University of Hawaii

PROFESSIONAL AFFILIATIONS: American Business Women's Association, Ilima Chapter, 1974  
Executive Secretaries, Inc. (Past Member)  
National Secretaries' Association (Past Member)

JOHN W. SHUPE

Dean of the College of Engineering

Professor of Civil Engineering

EDUCATION:

B.S., Kansas State University, 1948  
M.S., University of California at Berkeley, 1951  
Ph.D., Purdue University, 1958

PAST EMPLOYMENT:

1943-1946	Navigator, U.S. Air Force, European Theatre of Operations
1948-1949	Instructor, Applied Mechanics, Kansas State University
1949-1951	Lecturer in Civil Engineering and Junior Engineer in the Institute of Transportation and Traffic Engineering, University of California at Berkeley
1951-1953	Assistant Professor, Applied Mechanics, Kansas State University
1953-1954	Structures Engineer, Consolidated-Vultee Aircraft Corporation, San Diego, California
1954-1956	Associate Professor, Engineering, Kansas State University
1956-1958	Graduate Fellow, Civil Engineering, Purdue University
1958	Research Engineer, Joint Highway Research Project, Civil Engineering, Purdue University
1958-1960	Associate Professor, Applied Mechanics, Kansas State University
1960 (summer)	Research Engineer, Hughes Aircraft Company, Culver City, California
1960-1965	Professor and Associate Dean, College of Engineering, Kansas State University
1961-1963	Acting Dean, College of Engineering, Kansas State University
1964-1965	Project Coordinator for the MASUA-AID Engineering Educational Program with the University of Assuit, Egypt
1965-1969 & 1970-Present	Dean of Engineering, University of Hawaii
1969-1970	Interim Vice President for Academic Affairs, University of Hawaii

OTHER ACTIVITIES:

Consulting: Water Quality Advisory Board, City and  
County of Honolulu  
Member of the Governor's Environmental Council  
Member of the State Energy Policy Task Force  
Chairman of the State Committee on Alternate Energy Sources  
for Hawaii

JOHN W. SHUPE (2)

PRINCIPAL PUBLICATIONS OF LAST FIVE YEARS:

"Low Density Energy Sources" - Proceeding, Adaptive Technology Conference  
on Low-Cost Housing. East-West Technology and Development  
Institute, Honolulu, July 1973.

"Geothermal Power for Hawaii - Phase I" - Proceeding, United States-Italy  
Cooperative Research Seminar on Geothermal Energy,  
University of Pisa, Italy, November 1973.

"The Hawaii Geothermal Project - Year One Overview" - Geothermal Energy  
Magazine, July 1974.

PROFESSIONAL SOCIETIES:

American Society of Civil Engineers  
American Society for Engineering Education  
National Society of Professional Engineers  
Hawaii Society of Professional Engineers  
Marine Technology Society

GEORGE P. WOOLLARD

Director, Hawaii Institute of Geophysics  
Professor of Geophysics

EDUCATION: Postdoctoral, Lehigh University, 1938-1939  
Ph.D., Princeton University, 1937  
M.A., Princeton University, 1935  
M.S., Georgia Institute of Technology, 1934  
B.S., Georgia Institute of Technology, 1932

PAST EMPLOYMENT:

1926-1932	Co-op Student, Georgia Tech. (clay products, mining, dam and power plant construction, water works operations with various companies)
1932-1934	Graduate Assistant (Experimental Engr.) Georgia Institute of Technology
1936	Graduate Assistant, Petrology, Princeton University
1940	Lecturer, Geophysics, Rutgers University
1941	William Pierson Field Lecturer, Geophysics, Princeton University
1942-1948	Research Group Leader in Underwater Acoustics, Woods Hole Oceanographic Institution
1948-1963	Associate Geophysicist and Oceanographer, Woods Hole Oceanographic Institution
1948	William Pierson Field Lecturer, Geophysics, Princeton University
1952-1963	Associate Professor and Professor of Geophysics and Engineering Geology, Department of Geology and Geophysics, University of Wisconsin
1957-1963	Professor of Geophysics and Director, Geophysical and Polar Research Center, University of Wisconsin
1963-Present	Professor of Geophysics and Director, Hawaii Institute of Geophysics, University of Hawaii

HONORS: University of Hawaii Excellent in Research Award (1971)  
Honorary Doctorate, University of Uppsala, Sweden (1973)  
William Bowie Medal, American Geophysical Union, Washington, D. C. (1973)

OTHER ACTIVITIES: (Partial and Abbreviated Listing)  
Member, American Geophysical Union  
Member, National Academy of Sciences  
Member, Governor's Advisory Committee on Science & Technology  
Member, State Committee on Alternate Energy Sources for Hawaii  
U. S. Representative on Int'l Gravimetric Bureau

George P. Woollard (2)

PRINCIPAL PUBLICATIONS OF LAST TEN YEARS

Gravity: Research in Geophysics (H. Odishaw, Editor), Chapter 8, MIT Press, pp. 195-221, 1964.

Problems of the Upper Mantle and Hawaii as a site for the Moho Hole: Pacific Science, Vol. XIX, No. 3, pp. 271-284, 1965.

(With L.W. Kroenke) Gravity investigations on the Leeward Islands of the Hawaiian Ridge and Johnston Island: Pacific Science, Vol. XIX, No. 3, 361-366, 1965.

(With W.E. Strange, J.C. Rose) An analysis of the gravity field over the Hawaiian Islands in terms of crustal structure: Pacific Science, Vol. XIX, No. 3, 381-389, 1965.

(With A. Malahoff) Magnetic measurements over the Hawaiian Ridge and their vulcanological implications, Bull. Volcanologique, Vol. 29, pp. 735-760, 1966.

(With A. Malahoff, W.E. Strange) Molokai fracture zone: Continuation west of the Hawaiian Ridge, Science, Vol. 153, No. 3735, pp. 521-522, 1966.

(With W.E. Strange) The prediction of gravity, in Gravity Anomalies: Unsurveyed Areas, Geophys. Mono. No. 9, pp. 96-113, 1966.

Regional isostatic relations in the United States in John S. Steinhart and T. Jefferson Smith (eds.), The Earth Beneath the Continents, Am. Geophys. Union Mono. No. 10, pp. 557-594, 1966.

Crust and mantle relations in the Hawaiian area, in W.H. Poole (ed.), Continental Margins and Islands Arcs, Geol. Surv. Canada Paper 66-15, pp. 294-310, 1966.

Gravity measurements in S.K. Runcorn F.R.S. (ed-in-chief), International Dictionary of Geophysics, Vol. 1, Pergamon Press Ltd., Oxford, pp. 687-693, 1967.

Continental structure of Antarctica, Ann. Int. Geophys. Year. Vol. XLIV, pp. 122-143, 1967.

(With J.C. Rose, A. Malahoff) Marine gravity and magnetic studies of the Solomon Islands, in Leon Knopoff, Charles L. Drake, and Pembroke J. Hart (eds.), The Crust and Upper Mantle of the Pacific Area, Geophys. Mono. No. 12, Am. Geophys. Union, Washington, D.C., pp. 379-410, 1968.

The interrelationship of the crust, the upper mantle and isostatic gravity anomalies in the United States, in Leon Knopoff, Charles L. Drake and Pembroke J. Hart (eds.), The Crust and Upper Mantle of the Pacific Area, Geophys. Mono. No. 12, Am. Geophys. Union, Washington, D.C., pp. 312-341, 1968.

(With M.H. Manghnani) Elastic wave velocities in Hawaiian rocks at pressures up to 10 kilobars, in Leon Knopoff, Charles L. Drake, and Pembroke J. Hart (eds.), The Crust and Upper Mantle of the Pacific Area, Geophys. Mono. No. 12, Am. Geophys. Union, Washington, D.C., pp. 501-516, 1968.

(With L.W. Kroenke) Magnetic investigation in the Labrador and Scotia Seas, USNS ELTANIN Cruises 1-10, 1962-1963, Hawaii Institute of Geophysics Report 68-4, (115 pp.) 1968.

A geophysical analysis of gravity and magnetic data, Hawaii Institute of Geophysics Special Report, (175 pp.) 1968.

George P. Woollard (3)

PUBLICATIONS (continued)

(With A.S. Furumoto, J.E. Campbell, D.C. Hussong) Variation in the thickness of the crust in the Hawaiian Archipelago, in Leon Knopoff, Charles L. Drake and Pembroke J. Hart (eds.), The Crust and Upper Mantle of the Pacific Area, Geophys. Mono. No. 12, Am. Geophys. Union, Washington, D.C., pp. 94-111, 1968.

Regional variations in gravity, Geophys. Mono. No. 13, Am. Geophys. Union, Washington, D.C., pp. 320-340, 1969.

Tectonic activity in North America as indicated by earthquakes, Geophys. Mono. No. 13, Am. Geophys. Union, Washington, D.C., pp. 125-133, 1969.

Evaluation of the isostatic mechanism and role of mineralogic transformers from seismic and gravity data in Upper Mantle Symposium Proceedings, Canberra, Australia, Physics Earth Planetary Interiors, 3, pp. 484-498, 1970.

(With M.A. Khan and K.I. Daugherty) Statistical analysis of the relation of marine gravity anomalies to bathymetry, Final Report 1970-1971, ACIC Contr. No. F23601-71-C-0100, 22 figs., 51 tables, Hawaii Institute of Geophysics Report 71-20, (141 pp.) 1971.

The geophysical setting of the Hawaiian Ridge and implications concerning its origin, p. 264 in Geol. Soc. Am. Abstrs. with Programs, 1972. Presented at the 68th Annual Meeting of the Geological Society of America, Cordilleran Section, March 1972 (Honolulu, Hawaii)

(With M.A. Khan) Prediction of gravity in ocean areas, Final Report 1971-72, ACIC Contract F23601-71-A-0187, Hawaii Institute of Geophysics Report 72-11.

(With D.A. Walker, G.H. Sutton, N.J. LeTourneau and E. Kausel) Easter Island seismograph observations indicative of sea-floor spreading; plate edge seismicity relationships; and the prediction of earthquakes along the West Coast of the Western Hemisphere, NSF Grant GA-12851, 22 figs., 7 tables, Hawaii Institute of Geophysics Report 72-2 (54 pp.) 1972.

(With H.C. Marsh and R. L. Longfield) A comparison of observed and predicted earth tide observations between Alaska and Mexico and across the zone of crustal transition between Nebraska and Utah, Dept. of Army Contract DACA 71-67-C-0010 (52 pp. + Append.) 1973.

SOCIETY MEMBERSHIPS:

Princeton University Fellow (1936-1937)

American Geophysical Union Fellow (1937-1938)

National Research Council Fellow (1939-1940)

Guggenheim Fellow (1940-1941 and 1947-1948)

Nat'l Research Council Certificate of Merit

Member, Cosmos Club (1948-present)

Fellow, Geological Society of America

Fellow, Royal Astronomical Society

Fellow, American Association for Advancement of Science

Fellow, Mexico Geophysical Union

Society of Exploration Geophysicists

Association of Petroleum Geologists

European Association of Exploration Geophysicists

American Institute of Mining and Metallurgical Engineers

Seismological Society of America

Hawaiian Academy of Sciences

Tau Beta Pi

Sigma Xi

Phi Kappa Phi

Omicron Delta Kappa

## Hawaii Geothermal Project - Geophysical Program

Principal Investigator: Augustine S. Furumoto

### A Proposal for Continuing Geophysical Exploration in Search for Geothermal Sources on the Island of Hawaii

#### I. INTRODUCTION

The following is a proposal to the National Science Foundation, Research Applied to National Needs, to continue geophysical and other surface exploration studies in connection with the investigation of geothermal sources on the island of Hawaii. The work proposed is in continuation of that started this past year under NSF grant GI-38319 for the Hawaii Geothermal Project. Specifically, the funding is requested to: (a) complete and augment the exploratory phase of study required before undertaking the research drilling phase, and (b) to carry out interpretative downhole geophysical measurements once the drilling phase is underway. While drilling is in progress, investigators will monitor the areas of particular concern. After drilling has been completed in a hole they will attempt to correlate the drilling data with the surface survey data and to interpret the two in terms of subsurface geothermal conditions and enclosing structure.

As mentioned elsewhere in this proposal, the areas of interest for the project are the East and Southwest Rift Zones of Kilauea Volcano and the Southwest Rift Zones of Mauna Loa. For the geophysics program, the East Rift Zone of Kilauea is of prime interest. The East Rift is the testing ground, the research laboratory to find out what geophysical parameters mean in terms of geothermal energy. Surveys in other areas will be interpreted in terms of the results from the East Rift.



The East Rift Zone is located in the geographical area known as the Puna District. In fact the Puna District is almost coextensive with the flanks of the East Rift Zone. Hence in our proposal, Puna District will mean for practical purposes the flanks of the East Rift Zone.

The present proposal is organized on the basis of the following sections:

Section II - A summary of geological and geophysical study in the Puna area

Section III - Results of geophysical surveys carried out the previous year under the Hawaii Geothermal Project

Section IV - Proposed types of studies for the coming year

Section V - Description of geophysical tasks: personnel, method, time table; and an itemized budget

The Hawaii Geothermal Project is of more than parochial interest and has many far reaching applications to the geothermal study of other areas. This is clear from a consideration of plate tectonics theory. According to this theory, material from the deeper parts of the mantle upwells along oceanic rift zone crustal spreading center. The ocean floor and lithosphere thus move along in a giant conveyor belt type motion and then plunges back into the mantle at points of crustal convergence marked by island arcs and continental margins marked by oceanic trenches, which are called subduction zones. Most of the volcanoes of the world occur along subduction zones. To explain the Hawaiian volcanic archipelago which occur in the middle of the Pacific ocean, where there is no subduction zone, but where mantle material nevertheless has broken through the lithosphere and the ocean floor, other mechanisms must be postulated. One is that it represents the consequence of the Pacific crustal plate migrating across a "hot spot" in the mantle. Under this concept there is only one center of volcanism (that now beneath the island of Hawaii), and the archipelago extending up to Midway

Island and possibly the Emperor Seamount Chain extending up to the Aleutians mark the trail of crustal migration. Another concept is that the archipelago represents the path of a crustal rift with active volcanism on its leading nose where the rift, as it grows like a crack migrating across a plate glass window, intersects cross cutting transform fault fractures. Either concept would satisfy the increase in age of the archipelago in progressing along it from the island of Hawaii where there is present volcanism. The last though would have a point in common with spreading centers in that volcanism would occur where there is an opening in the crust and reduction in confining pressure. Volcanism ceases when the opening is sealed off by the extruded material plugging the opening and building up sufficient pressure beneath the volcanic pile to stop the flow of lava. This is true of old spreading centers, as well, when the regional stress pattern causes a spreading center to "jump" as in the case of the East Pacific Rise which is a young feature and was preceded by what is now a "fossil" spreading center located in the middle of the Nazca Plate off Peru. The enechelon pairs of separated major volcanic centers on most of the Hawaiian islands is a strong argument for their having formed at fracture intersections with one fracture system being a migrating one. Another argument is that the high heat flow is confined to the volcanic pile and has no regional extent as might be expected with a "hot spot" having a deep seated source, and another the marked similarity between Hawaiian lavas and those found in association with the crustal plate spreading centers.

The Hawaiian volcanoes could thus bear more than a superficial resemblance to the East Pacific Rise spreading center, and studying Hawaiian volcanoes could have a direct bearing on the study of East Pacific Rise and also on areas as the Salton Sea geothermal area, which overlies the landward extension of the East Pacific Rise beneath the North American continent. As Hawaiian volcanoes are exposed at ground surface, they can be readily studied and experiments performed

which would be difficult, if not impossible, elsewhere. The experience gained on the Geothermal Project will thus be applicable to the study of other potential geothermal areas as those on spreading centers as well as island arc subduction zones and other areas of volcanism.

## II. BACKGROUND INFORMATION ON KILAUEA EAST RIFT OF THE PUNA DISTRICT

Kilauea Volcano on the island of Hawaii has two rift zones, the East Rift and the Southwest Rift. The East Rift saw flank eruptions in 1955 and 1960, the Southwest Rift was active in 1971. The East Rift, together with the summit caldera area, has been intensely studied by members of the U.S. Geological Survey. Lately staff members of the Hawaii Institute of Geophysics, University of Hawaii, have carried out surveys along the East Rift.

The East Rift Zone starts off from Kilauea Caldera in a southeasterly direction, and then about 8 or 9 km from Kilauea Crater, the rift zone makes a nearly right angle bend, and heads in a east north east direction to enter into the sea at Cape Kumukahi. Along the rift zone are pit craters, cinder cones, open cracks in the ground and some steaming vents. That part of the rift zone close to Kilauea Caldera is within the Hawaii National Park and this area will not be the subject of investigation of the present proposal. But a 30 km stretch of the rift zone is outside the park boundaries and cuts across what is geographically called the Puna District. Our proposed survey will cover the greater part of the Puna District.

It is impossible to give in this report a good review of past studies in the Puna Area because of the voluminous amount of information. A summation will be presented here and then the present state of the problem will be given.

Geology. The geology of Puna area has been done as part of the study of Kilauea Volcano (Stearns and Macdonald, 1946; Macdonald and Abbott, 1970). It is thought that a platform formed by Mauna Loa lava flows underlies Puna area, and

on this platform lie the lava flows and ash deposits from Kilauea. Puna area also has a number of faults parallel to the East Rift Zone.

Geodetic Survey. Comparison of geodetic survey data since 1914 to the present showed that the entire south flank of Kilauea Volcano, of which Puna District is a part, has been displaced seaward for 4.5 meters (Fiske and Kinoshita, 1969). If the seaward slump proceeds at a constant rate, this means a creep of about 8 cm per year. It seems that the slump is more spasmodic in nature.

Gravity Survey. Gravity survey by Kinoshita (1965) showed that the east rift in general had a Bouguer anomaly of about 10-20 mgals above the regional. A survey with closer spacing by Hawaii Institute of Geophysics indicate that the high of the anomaly lies to the north of the rift rather than over it.

Deformation study. From careful surveys in elevation changes, Decker (1974) concluded that the east rift is dipping southward at an angle of  $45^{\circ}$ . This theory of a dipping rift zone will be checked by our proposed study.

Passive Seismic Observations. Earthquakes in the Puna area occur south of the rift zone, only a few to the north of it. Koyanagi, Swanson and Endo (1972) proposed that the earthquakes are due to the slumping of the south flank. There are times when earthquakes are concentrated in a very small area. These are probably due to magmatic action.

Ward and Gregerson (1973) used a tripartite array of sides 1 to 2 km long to determine hypocenters south of Kilauea Volcano. They concluded that events within 5 to 10 km from the array can be determined accurately. They also found that S waves were poorly recorded. Some focal mechanism solutions were also obtained.

Ground noise surveys have also been carried out. Keller's (1974) results claim that 4 hertz ground vibrations are high over areas where electrical surveys showed low resistivity. However surveys carried out by Hawaii Institute of Geophysics do not show such variations, but that the 4 hertz noise dies away from the shoreline.

Active Seismic Survey. Hill (1969) proposed a crustal structure for the Puna area from seismic refraction data. As he did not have close in shots in his survey, he assumed that the first layer had a P-wave velocity of 1.8 km/sec and a thickness of 0.7 km. The second layer had a velocity of 3.1 km/sec and extended from a depth of 0.7 km to 2.3 km. The layer below that had a velocity of 5.3 km/sec.

Magnetic surveys. Magnetic surveys were carried out over Puna several years ago (Malahoff and Woollard, 1968). The results show that there is little magnetic expression over Puna, due to the high temperature of the rift zone.

Electrical Surveys. Keller (1973) carried out a dipole-roving dipole type electrical resistivity survey over the area. The most probable interpretation was a model of two layers overlying a half space of infinite resistivity. The first layer had a thickness of 700 m with resistivity of about 20 ohm-m., the second layer extended from 700 m depth to a depth of about 2.2 km with a resistivity of about 5 ohm-m.

Recent survey by Klein (1974) showed that the near surface rock without water has a resistivity of about 6000 ohm-m and at the water table the resistivity can be as low as 1 ohm-m.

Self potential surveys by Zablocki (1974) made apparent two anomalies on the rift zone, each providing a voltage gradient of several hundred millivolts per 100 meters. The anomalies are positive poles.

Thermal Surveys. There were many wells drilled in the area in search for agricultural water. Temperature measurements made in these wells indicate that higher temperatures occur near the rift zone. Heat flow measurements have not been made.

Geochemical Surveys. Water samples from many of these well have been analyzed for oxygen isotope content. (McMurtry and Fan, 1974). The interpretation of the results is that the groundwater in the region has one through a thermal region at least 200°C.

undetected because they have been covered over by lava flows or thick vegetation. The best way to locate such hidden faults are by seismic reflection techniques.

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### III. Results of Geophysical Exploration During the period May 1, 1973 to Present (June 1, 1974), A Progress Report

Upon receipt of Grant GI-38319 from the National Science Foundation and matching grants from the State and County of Hawaii, the geophysical exploration program was initiated. Since the Institute of Geophysics did not have some of the equipment necessary for the proposed work, certain aspects of the proposal such as the Infrared study and the preliminary electrical investigation were contracted out to groups able to start work immediately, since a delay of at least six months could be expected in getting delivery on equipment. At about the same time, George Keller of the Colorado School of Mines, was drilling an exploratory hole in the National Park area of Kilauea Volcano. The information from that drilling project as it progressed provided much useful information of value to the geophysical program.

Because of limitations of funding, only the following types of surveys were planned to be carried out during the first year:

1. Aerial infrared survey covering geologically favorable areas
2. Electrical resistivity surveys of the Puna rift area using the dipole method
3. Electromagnetic surveys of selected areas
4. Microseismic and microearthquake surveys

The aerial photo surveys were the responsibility of Agatin Abbott. The work was contracted to Towill Corporation. Results were available by September 1973.

The dipole electrical resistivity survey for reconnaissance purposes was in by August 1973.

The electromagnetic surveys were under the supervision of Douglas Klein. As all of the equipment had to be built, the field work started late and is still underway at the time of writing of this proposal.

The microearthquake surveys, under the supervision of A.S. Furumoto, got off to a late start because of over eight months delay in getting delivery on equipment. Because of this, the schedule outlined in the original proposal was impossible to maintain. The original proposal planned for surveillance of microearthquakes first, then ground noise surveys. But as instruments for the microearthquake system were not delivered by the manufacturers until February 1974, the ground noise survey was done first, without the benefit of data from the expected microearthquake survey.

Although every economy was made in carrying out the initial phase of surface investigation, including skimping on per diem and borrowing equipment, in January 1974 it became clear that all the proposed cannot be completed with the remaining funds. A decision was therefore made to postpone a major portion of the seismic surveys and redistribute the funds so that the other surveys could be brought to fruition with maximized results. As for the seismic surveys, a reconnaissance ground survey was carried out and the instrument system for microearthquake surveillance was carefully calibrated and field tested on Oahu.

In the following section, short descriptions of the accomplishments of each task are given. For more details, the reader must await the publication of progress reports.



## 1. Photogeologic Survey

Investigator: A. T. Abbott

Imagery from Infrared Scanning of the East and Southwest Rift  
Zones of Kilauea and the Lower Portion of the Southwest Rift  
Zone of Mauna Loa, Island of Hawaii

### INTRODUCTION

From July 31 through August 4, 1973 night time flights for obtaining infrared imagery along the east and southwest rift zones of Kilauea and the southwest rift zone of Mauna Loa were undertaken on the island of Hawaii. Flights were also made on Hualalai and Kohala volcanoes, but because of inconclusive results are not included in this report. Ground control stations had been established during daylight hours several days prior to starting the flight program. Students stationed at the ground central points guided the aircraft on predetermined flight paths by the use of directional lights which were visible to the plane's navigator. Results of the infrared scanning program are considered to be very successful. Events leading up to the final imagery on 8 x 10 color prints will be discussed below.

The sum of \$23,900 was designated by the NSF to be expended on aerial photogeologic work on the Hawaii Geothermal Project. Infrared scanning was the only aerial technique employed in this phase.

A firm specializing in infrared surveys, Daedalus Enterprises of Ann Arbor, Michigan was selected as best equipped and experienced in Hawaiian conditions to accomplish the infrared imagery survey. Towill Engineering Corporation of Honolulu provided the aircraft, pilot and navigator and submitted a report with maps and black and white aerial photographic mosaics. These firms earlier the

same year had flown paths for Dr. George Keller of the Colorado School of Mines, who was engaged in locating a deep drill hole near the summit of Kilauea.

## FLIGHT PATHS AND DESCRIPTIONS

### (1) East Rift Zone of Kilauea

Two long parallel flight paths were flown along the East rift zone from points outside the boundary of Hawaii Volcanoes National Park to Cape Kumukahi. Shorter paths crossing the two long parallel lines were flown at the intersection of the rift zone with the main highway between Pahoa and Kalapana. Approximately 35 line miles of usable record was obtained. From this the following strips were selected for reproduction in infrared false color imagery:

Three miles of flight paths high on the rift zone at an average ground elevation of 2100 feet provide excellent examples of rift lineation and temperatures aureoles. The DIGICOLOR prints showed a temperature range of  $14^{\circ}\text{C}$  to  $20^{\circ}\text{C}$ . Numerous sites along the rift showed spots of white color indicating the temperature exceeded the highest range on that temperature set. This is not surprising in view of the fact that wisps of steam are issuing from some of the vents probably as a result of meteoric water coming in contact with residual heat of lavas from the 1966 eruption in this area. Downslope from the steam vents, a fairly extensive area shows a slightly higher surface temperature than its surroundings, by an average of  $1^{\circ}\text{C}$ .

The area for the second set of DIGICOLOR prints in the Kilauea east rift zone was selected from a flight path of approximately two miles in length across the area of intersection of the rift zone and the Pahoa-Kalapana highway at a ground elevation of approximately 3000 feet. The temperature range of this path is  $16^{\circ}\text{C}$  -  $25^{\circ}\text{C}$  or  $1.5^{\circ}\text{C}$  per color. Again numerous sites showing white along the rift zone indicate local hot spots and an aureole of decreasing temperatures

are distributed outward from the rift. Fine examples of surface temperature zones are demonstrated in this imagery.

## (2) Southwest Rift Zone of Kilauea

A flight path 12 miles long was followed from the point of intersection of the western boundary of Hawaiian Volcanoes National Park and the main highway between Kilauea summit to Pahala to a point on the sea coast approximately 4 miles east of Punaluu.

The altitude maintained was about 3000 feet above ground level. Throughout most of the strip a thermal anomaly was evident along the Great Crack. The temperature range on the flight path was  $18^{\circ}\text{C}$  -  $22^{\circ}\text{C}$ . Of unusual interest on this path is a thermal anomaly in a target-like pattern near the southern end of the Great Crack approximately 1 1/4 miles from the coast line at an elevation of 300 feet above sea level. The target-like pattern is 1200 feet wide, 1600 feet long. The roughly circular pattern of thermal anomaly lies 600 feet northwest of a splinter extension of the Great Crack. The highest temperature within the target area reaches the red color or  $22^{\circ}\text{C}$  in two small spots, and within the Great Crack extension, small local spots reach white, or off scale.

The anomaly appears to be associated with the lower slopes along the south side of Puu Kolekole, a prehistoric cinder cone, and with the extension of the Great Crack.

This surface thermal anomaly as registered by infrared scanning imagery should receive careful attention as a potential area for further geophysical investigation and possibly research drilling.

## (3) The Southwest Rift Zone of Mauna Loa

A flight path with the total length of approximately 22 miles followed the southwest rift of Mauna Loa from an elevation of approximately 7000 feet above sea level to the tip of South Point. Only the lowest five mile section of

this path to the tip of South Point showed any significant thermal anomalies. This portion has been reproduced in DIGICOLOR and prints developed.

The temperature range on one subset is  $16^{\circ}\text{C}$  -  $22^{\circ}\text{C}$ . Thermal anomalies appear along the cliff face of the Kahuku fault as clusters along the base of the cliff and as linear features possibly indicating bedding planes in the lava flows. Numerous spots along the cliff register red and a few local areas show white, or off scale.

The cause of these anomalies is not known at the present time. The Kahuku fault scarp, which reaches 400 feet in height in this area, faces west. Consideration must be given to the possibility that the anomalies result from residual late afternoon solar heat. The imagery was taken at 0030 hours in order to reduce the effect of residual heat. The physical distribution of the warmer areas does not appear to show a pattern that might be caused by residual heating, none the less this factor must be kept in mind.

Another, more intriguing possibility lies in the concept that heat may be rising from depth along the plane of the Kahuku fault and issuing at the base of the cliff and along bedding planes of the lava flows. The Kahuku fault is a major structural feature of Mauna Loa shield volcano. It extends ten miles inland from the coast and has been followed out to sea for a distance of over 15 miles. Depth recordings made on board the R/V VALDIVIA in 1973 while steaming past the extension of the fault 4 miles off shore registered a vertical displacement along the fault plane of 1900 meters.

Further geophysical and geological work should be concentrated in the section of the lower portions of the Kahuku fault. This may have promise as an area in which to locate an array of research drill holes.

Also of interest along the South Point shoreline as registered by the infrared imagery is the temperature distribution in the sea water. Directly offshore a large patch of water shows as a white area indicating that its temperature is

greater than  $22^{\circ}\text{C}$ . It is not recognized at this time whether this is a bay of warm surface water brought in by ocean currents or wind or whether the warming is caused by some other process.

## 2. Electrical Resistivity Surveys

Investigator: G. V. Keller

Report by: A. S. Furumoto

The electrical resistivity surveys by George Keller were done in June and July 1973 and a report entitled "An Electrical Resistivity Survey of the Puna and Kau Districts, Hawaii County, Hawaii" was submitted by him. The method he used is known as the dipole mapping method. In short, using existing well casings as dipole sources, he caused a large amount of current to flow into the ground, then with a pair of probes the area round the dipole source was surveyed to measure variations in voltage and current. With that, resistivity of the ground between the dipole source and probes is determined. The survey in effect gives an integrated picture of resistivity with respect to depth. Hence the method is a good reconnaissance tool.

The results of the survey came up with two promising areas indicating subsurface low resistivity. Both of these areas lie along the Northeast Rift zone of Kilauea. In Figure 1 the circled area roughly outlines the low resistivity anomaly.

Keller also attempted a depth vs. resistivity interpretation from his data. The profile resulted in a two layer model; the first layer extending from surface to an average depth of 700 m with resistivity about 20 ohm-m; the second layer extending from 700 m to 2300 m depth with resistivity about 5 ohm-m; and below that a half space of very high resistivity. Keller attributed the low resistivity in the second layer to high temperature.

### 3. Electromagnetic Survey

Investigator: D. P. Klein

1. The electromagnetic survey group of the Hawaii Geothermal Project can report the following accomplishments:

- a. Completion of a loop-loop magnetic induction survey in the northeast Puna area.
- b. Development of a deep-sounding wire-loop magnetic induction system.
- c. Reconnaissance of four areas on Hawaii Island (excluding Puna) which have promising geothermal aspects.
- d. Emplacement of 12 electrode pairs for future deep geoelectric sounding on Hawaii Island.

2. The two-loop induction survey in the Puna area was a follow up to the dipole-dipole galvanic survey of G.V. Keller and associates. The results of Keller's survey which warranted further exploration was the possible existence of shallow geothermal regions in the areas outlined by the dashed lines in Fig.

1. High temperature well waters in these areas add support to such a possibility. The two-loop soundings, whose locations are indicated in Fig. 1, were established with the object of locating the extent of the regions of high conductivity, thus potentially hot water, in the upper 100 meters of the crust. The results were negative in this regard. Local conductivity anomalies at stations 18-1, 19-1, 20-1 and station 6-1, and 3-1, 3-2 could be due to heating effects along the East Rift zone or due to increased porosity associated with Rift fissures. However, the existence of shallow high temperature areas of large horizontal extent are not in evidence. It is recommended that detailed "deep" geoelectric surveys be carried out in the anomalous areas mentioned above, under the hypothesis

that these regions are shallow indicators of a wider spread geothermal regions at depth.

3. In view of the need for deeper penetrating equipment a concentrated effort went into the construction of a power source for a time-domain wire-loop induction method. This power source will provide approximately a 20 amp current-step square wave at 1000 VDC. The system is essentially complete except for field tests. The system is solid state and built to withstand rugged field conditions. The expected depth of penetration of this system is about two kilometers.

4. In anticipation of future operations, four areas on Hawaii were examined in detail for survey sites. These areas, indicated on Fig. 2 (Task 2.2, Geoelectric, of the proposal) were chosen with regard to the rift zone location, age of most recent volcanic activity, available drill hole temperature data and the results from the infrared scanning study.

5. Since the effective use of the wire-loop induction technique requires low resistance electrical earth-grounds, 12 electrode pairs were emplaced for the future surveys. Seven of these were emplaced by Sandia Corporation using a technique of air-dropping specially designed inert-missiles. The reason for early emplacement of electrodes is that the contact resistance can be expected to decrease with age due to natural processes causing closer compaction of earth about the electrodes. Although more electrodes will probably be required, at least future surveys can begin with the several good source field sites now established.





#### 4. Microearthquake and Microseismic surveys

Investigator: A. S. Furumoto

Although it was planned to carry out microearthquake surveys during the first year, it was decided to postpone these surveys until the second year. The main reason for this decision was the delay in getting delivery on equipment and that funds were being used up at a higher rate than anticipated in running the other surveys. In the final analysis it was judged better to obtain excellent results from three types of surveys than obtaining marginal data from four types of surveys.

However, the equipment for the microearthquake surveillance program purchased is now assembled and undergoing tests. The seismic surveillance system consists of a central recording station and six satellite stations. At a satellite station seismic signals picked up by geophones are amplified, frequency modulated, and then telemetered by radio to the central recording station. Data is recorded on tape at the central station.

For the microseismic or ground noise survey, a simple system was devised. The instrument package consists of two geophones, an amplifier bank, and a TEAC R-70 cassette tape recorder which can record in FM mode or in direct analog form. The package is small enough to be housed in the backseat of a compact car.

With the above instrument package, the eastern section of Puna district was surveyed on a preliminary basis for ground noise. Two days of recording were made on eight reels of cassettes. For data processing, many techniques were tried; such as digitizing the records followed by power spectrum analysis by computer; use of machine frequency analysis. These were unsatisfactory as sampling or frequency resolution was poor. The best results were obtained by sending

the taped signals through narrow band filters and obtaining rectified, averaged power levels. By this technique it was found that the 8 hz ground noise centered around the electrical resistivity anomalies found by Keller. Whether this is also diagnostic of geothermal sources is yet to be determined.

Ground noise surveys are presently being carried out over the Puna area and the southwest rifts of Kilauea and Mauna Loa.

## 5. Other Surveys. 1973-1974

Report by: A. S. Furumoto

In addition to the fore mentioned surveys, several other types of surveys were undertaken.

Although gravity surveys over the Puna area were carried out about a decade ago, the grid was rather coarse. So, in May 1974 a closely spaced traverse was made across the Puna Rift. Time was available for only one traverse as the work was done in between electrical surveys. Even with the single traverse, a significant bit of information was found. The high positive point of Bouguer anomaly is not over the rift zone but to the north of it. This does not lend support to Decker's postulate that the rift zone is dipping to the south. However this does not contradict Decker as the mass in the rift zone is not much denser than the surrounding rock.

Magnetic surveys by traverses on the ground surface were also done. There was little variation in the magnetic field, an indication that the rift zone material is very hot, above the Curie Point.

Independent of this project, Zablocki of Hawaii Volcano Observatory carried out a self-potential electrical survey in the Puna area. Two anomalies of several hundred millivolts per 100 m were found, coinciding with Keller's low resistivity anomalies. These are encouraging signs. At the present time, technicians and students on this project are assisting Zablocki to complete the self-potential survey of Puna area. Data from this cooperative will be available to the project.

The water in the presently existing wells in Puna area were sampled and were analyzed for oxygen isotope content at the laboratories of University of California at Riverside. The analysis at Riverside were done by a graduate

student from this project who traveled to Riverside. The conclusion of the analysis is that the water had a past history of being heated to 200°C or more. This task was carried out under the direction of Dr. P. F. Fan.

As additional funds were promised by the National Science Foundation to continue the program until the end of calendar year 1974, a full schedule of surveys has been planned for the summer months. The Schedule runs as follows:

June

- Self potential electrical survey
- Electrical resistivity survey
- Seismic ground noise survey
- Geochemical survey, oxygen isotope and deuterium

July

- Electrical resistivity surveys
- Laboratory study of convection in porous media, theoretical study and modelling
- Literature survey

August

- Microearthquake surveillance
- Thermal survey of wells
- Electrical resistivity surveys

## 6. Resulting Publications

The present time is too early for results of the field surveys to see the light of publication. The infrared scanning survey is the only one of the field work that is in publishable form. However, literature survey and compilation of published articles on the Koolau Volcano on the island of Oahu, Hawaii and on the Rabaul Volcano on the island of New Britain, Papua New Guinea, were done and papers on them were presented at the U.S.-Japan Cooperative Science Seminar held in Hilo, Hawaii during the week of February 4-8, 1974. The papers will be published in the Proceedings of the seminar. The authors and titles of publications resulting from the project or supported by the project are:

- A. T. Abbott - Imagery from Infrared Scanning of the East and Southwest Rifts of Kilauea and the Lower Portion of the Southwest Rift of Mauna Loa, Island of Hawaii. Proceedings of the U.S.-Japan Science Seminar on Utilization of Volcano Energy, February 1974. Sandia Laboratories, 1974, (in press).
- A. S. Furumoto - Geophysical Exploration on the Structure of Volcanoes: Two Case Histories, Ibid. (In Press)
- A. S. Furumoto and W. A. Wiebenga - Possible Use of the Rabaul Volcanic Complex as a Source of Energy. Ibid. (In Press)

#### IV. PROPOSED WORK FOR 1975

The geophysical program of the geothermal project with funding through NSF GI-38319 is carrying out field surveys in high gear at the present writing of this proposal. As the field surveys will have been completed by September 1974, the present proposal will put emphasis on analysis and interpretation of the field data.

The types of field surveys and study that would be completed are more in number than what had been mentioned in the initial proposals. As data unfolded, different types of surveys were conceived and carried out to check the newly developing picture. The types of surveys being carried out are given below. Each survey involves different kinds of instrument and equipment and different ways of analysis. For example, the several surveys that involve electrical techniques are different from one another and each yields a distinct type of information.

The surveys and studies that were completed or are going on now are the following:

1. Infrared scanning aerial photography
2. Electrical resistivity reconnaissance by dipole-roving dipole method
3. Loop to loop electromagnetic method
4. Depth profiling for electrical resistivity by Schlumberger method
5. Self-potential electrical survey
6. Magnetic surveys on ground surface
7. Gravity survey
8. Seismic ground noise survey
9. Microearthquake epicenter location
10. Geochemical survey, oxygen isotope
11. Geochemical survey, deuterium
12. Thermal survey of wells

13. Convective motion in porous media, analytical and computer study
14. Convective motion in porous media, physical model study
15. Literature survey on geochemistry of Kilauea

The tasks responsible for these surveys with the names of investigators are the following:

Task 2.0 General Services and Coordination

A. S. Furumoto

Task 2.1 Photogeology

A. T. Abbott

Survey (1)

Task 2.2 Electrical Methods

D. P. Klein

Surveys (3), (4), (5),

Task 2.3 Modelling and Computation

R. Norris and A. S. Furumoto

Surveys (6), (7) and office studies (13) and (14)

Task 2.4 Temperature studies of wells

J. Halunen and D. Epp

Survey (12)

Task 2.5 Seismic Studies

W. Suyenaga and A. S. Furumoto

Surveys (8) and (9)

Task 2.6 Geochemistry

P. F. Fan

Surveys (10), (11) and (15)

Survey (2), electrical resistivity survey by dipole-dipole method, was subcontracted to G. Keller of Colorado School of Mines.

Of these, surveys (1), (2) and (3) are completed and final data are in;



surveys (6) and (7) are partially completed; surveys (5), (8) and (10) are being done in the field; surveys (4) and (9) are in the instrument testing stage; surveys (11) and (12) are being planned. The in-office studies (13), (14) and (15) are also presently being carried out.

After the field work during the months of June, July and August 1974, it is imperative that the data be analyzed, interpreted and digested. Even after the field data are in, the best way for processing the data has yet to be sought by trial and error. This takes time. For example, for the two days of field data in seismic ground noise survey, three months were used in finding the optimum system to process rapidly 15 hours of data tape. Various methods, such as digitizing analog records and then performing frequency analysis, were discarded as giving poor sampling. Several types of automatic machine analysis for spectrum were unsatisfactory. The method finally found to be satisfactory was to determine rectified power level at different frequencies by passing the recordings through narrow band pass filters. This example from seismic study shows that time spent in data processing in the office is usually an order of magnitude longer than the time spent in the field.

Also, along with field data, laboratory studies, theoretical studies, computer simulation, physical models must be tried to get the grasp of what is going on. For optimum results field men should cooperate closely with the model studies, in fact, it is best that they participate in it.

Some field programs are being proposed for this year, as drilling data may turn up added information which must be checked against geophysical surveys. Also, the southwest rift of Mauna Loa, which is presently being surveyed, should be examined carefully. A verbal report by A. T. Abbott says that the research vessel VALDIVIA measured the scarp of the rift at a point 4 miles at sea to have a 1900 m drop. Hence we are proposing a thorough geophysical survey of the seaward extension of that rift and other rifts with the University's research KANA KEOKI.

To round out the geophysical and geochemical information on the Puna Area two new tasks have been added to the geophysical program:

Task 2.7 Hydrology

Investigators: R.W. Buddemeier, P.M. Kroopnick, and L.S. Lau

Task 2.8 Physical Properties of Rocks

Investigator: M.H. Manghnani

Task 2.7 will attempt to unravel the hydrology of the Puna area relying mostly on geochemical data. This information is truly needed to understand the hydrothermal system which we are attempting to use for geothermal development.

Task 2.8 will undertake to measure the thermal conductivity of rocks as well as other physical properties of rocks from the Puna area. This is relevant to the program as initial calculations using reasonable temperature distributions and known values of permeability hint that there could be no convective motion of ground water in Puna Area away from the rift zones. Outside of rift zones the criterion of stability is not exceeded. If there is hot water below a depth of 700 m as Keller's reconnaissance survey tends to indicate (cf. previous chapter) then that water was most probably heated by conduction rather than by convective motion.

The geophysical program proposed will be a coordinated program of 8 tasks with 17 different surveys and studies. As the drilling gets underway, all involved will be on hand to assist with their specific area of knowledge and insight.

## V. INDIVIDUAL TASKS: PROPOSALS AND BUDGETS

### Task 2.0

#### General Operations Support and Coordination

The main purpose of this task has been to provide general services to the other geophysical tasks. The technician has the responsibility of assembling and testing instruments and later on maintaining them. The administrative assistant in the category of secretary-clerical handles the typing of manuscripts, the purchase orders, and accounting of the financial status of every task. The staff on this task have heavy duties and responsibilities.

As several field surveys are going on simultaneously during so called vacation times, the logistics must be coordinated. Field men from different surveys assist one another and the coordination is possible through a central clearing agency. The task does the work of such an agency.

## Task 2.2

### Geoelectric Surveys

Douglas P. Klein

#### INTRODUCTION

As a second proposed extension to NSF Grant GI-38319 the geoelectric task must be considered with two facts in mind. (A) The field results from the main survey are not in as this is written. (B) The evaluation of results of the main survey is not expected until at least September 1974.

The continuation of major geoelectric survey operations is contingent on the results obtained in the period from June 1 through December 31, 1974. Thus without anticipating those results, this task proposes only to complete a full final analysis of work accomplished to December 31, 1974, with allowance for 30 days field operations to obtain additional detailed data in those areas, if any, where initial data show anomalies of particular interest or where problems of interpretation arise because the initial data are too sparse.

#### JUSTIFICATION FOR ADDITIONAL DATA ANALYSIS

Analysis of geoelectric data up to December 31, 1974 will necessarily be of rudimentary nature due to the pressures involved in rapid selection of the most favorable targets for exploratory drilling. The extent of sophistication in depth-conductivity sections will be limited to two-layer interpretations<sup>(1)</sup> for electromagnetic work and three-layer interpretations<sup>(2), (3)</sup> for galvanic work. These are based on standard and limited two and three layer models. The

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(See footnotes at the end of this task description.)

electromagnetic interpretation in particular will be biased by the assumption of an idealized dipole source and receiver. It may not be difficult to make allowance for this, but in fact, the available interpretation schemes<sup>(1)</sup> are realized with this restriction.

We propose to approach possible improvements in the quantitative interpretation of data in this order: (A) Development of non-restrictive frequency domain and, time-domain solutions for loop-loop and loop-line electromagnetic soundings over horizontal layers, possibly along the line of Ryu<sup>(4)</sup>, and Morrison<sup>(5)</sup> and Koefoed<sup>(6)</sup>. (B) Multilayer (greater than three) modeling of the data obtained in Hawaii. (C) Development of direct inversion schemes for multilayer cases, possibly along the line of Glenn et al.<sup>(7)</sup> with the hope of obtaining quantitative resolution limits of the data with regard to layered structures. (D) Study of the influences of lateral inhomogeneities in earth strata on the interpretation of geoelectric data. This is probably the least well understood problem of geoelectric surveys, and except for extremely simplified models very few authors have attempted a quantitative development of this problem. One example is Yee<sup>(8)</sup>. A goal in this regard might be to work toward a numerical solution of an oscillating dipole field above a non-uniform conducting sheet. This is worked out for a plane-wave source<sup>(9)</sup> but not for a dipole field. Such a model could have applicability in the case of Hawaii where gradients in conductivity in the underlying salt water layer might be approximated by a thin sheet.

It should be pointed out that surface surveys will provide a wealth of field geoelectric data, and drilling program will provide a similar wealth of direct geological data from drill holes. This then will be an ideal opportunity to apply theoretical analysis to real data and compare the results to known conditions. From the standpoint of future exploration applications it seems vitally important to interpret the data to the fullest possible extent.

## JUSTIFICATION FOR ADDITIONAL FIELD WORK

In addition to obtaining more detail where possible over anomalies (if found) and over areas of questionable interpretation (if any) it seems important to obtain additional data in conjunction with the drilling program. As the initial surveys are reconnaissance in nature with the stated purpose of outlining the most favorable areas of drilling, additional surveys would serve the purpose of obtaining better resolution in the depth conductivity profile in the selected drill site areas. This would be important when direct geological drill data becomes available for comparison to geophysical data because it would establish the validity or non-validity of the geophysical techniques employed. This result would have direct significance to future geothermal exploration.

Another consideration is that if success is met in finding geothermal resources on the island of Hawaii it would be reasonable to begin reconnaissance of possible resources on other islands. In this case a decision would be required on the priority of shifting from further detailed work on Hawaii island to new surveys elsewhere. While the present proposed budget does not include sufficient funds to complete these surveys, preliminary work could be started simultaneously with a request for additional funds which could be evaluated on the basis of positive results.

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### Task 2.3

#### Theoretical and Numerical Modelling, Computational Geophysics, Magnetic and Gravity Surveys

A.S. Furumoto and R.A. Norris

The purpose of this task is to bring together all the geophysical data gathered in order to develop consistent models of the hydrothermal systems we are investigating. At this point in time the hydrothermal systems for the east rift of Kilauea and southwest rift of Mauna Loa seem to be two different things.

The task will first attack the hydrothermal system of the east rift of Kilauea. As data come in month by month, a clearer picture is evolving.

The question of convective fluid motion in a porous medium should be studied. Although there are numerical solutions to the problem, analytical studies of convective motion in porous media are not numerous. Numerical models may suffice but analytical models give deeper understanding. At the present time analytical studies of convective motion is being pursued.

Also, computational studies of the convective motion will be done. The boundary conditions of the problem will have to be changed with incoming data. The problem is very challenging.

Physical model studies using small tanks of water will also be tried. A tank is being built as of the present. Various kinds of material will be used as the porous medium: glass beads, sand, chips of plastic etc.

One parameter we have to know is the bulk permeability of the rock in Puna area. To do this we shall use the tidal effects felt in wells in the Puna area. From the velocity of the tidal effects through the rocks and the decay of tidal effects, the permeability of the rocks can be calculated. For measuring tides, tidal gauges are needed.



The task will also help with the computation problems of other tasks. The epicenter location program HYPO 71 to be used by Task 2.5 is being modified for the university computer.

The personnel in this task will also assist in field programs. R. Norris has been with the Hawaii Institute of Geophysics for over a decade and has carried out independent research.

The task will also complete the gravity and magnetic survey program with a dense network of observations. The magnetic data will require much tedious correction of data and, hence, will require a student helper.

## Task 2.4

### Temperature Survey

D. Epp and J. Halunen

This summer we will measure the variation of temperature with depth in existing wells on the island of Hawaii. Based on the results of this survey we will choose one or two wells in the Puna area and one or two wells in the South Point area for repeated temperature measurements. At this time we expect to measure the temperature variations with depth at least 20 times in each hole over a one year period. This temperature data will provide information on (1) rates of groundwater movement, (2) thermal conductivity of the rock adjacent to the upper 10-15 m of each hole, and (3) possibly past movements of magma in the area of each hole. All of this information is critical to evaluation of any geothermal power source.

Groundwater movement through the area around a well will upset the normal temperature gradient due to the earth's heat (see for example, Birch, 1947). Stallman (1963), Bradehoeff and Papadopulus (1965), Domenico and Palciauskas (1973), and others have shown that this deviation from the norm can be used to calculate the velocity of groundwater movement. Because of the high permeability of the islands and the low thermal conductivity of rock, groundwater movement is probably the dominant process that moves heat from the areas within the island that contain hot magma. If the hydrological system in the islands is largely an open system as proposed by Mink (1964), the heat from hot magma sources will be carried to the ocean by the moving groundwater. On the other hand, if closed systems exist within the island, the hot magma source will cause convection of the groundwater within the system. The proposed temperature surveys should allow us to determine which of these two systems exists in the Puna and South Point areas, and in addition, the velocity of groundwater movement within the system.

Similar temperature surveys will be an important part of the program to be conducted in conjunction with the deep exploratory holes to be drilled in 1976 and

1977. It is essential also that we determine whether the groundwater system at depth is open or closed. A proposal to fund periodic temperature surveys in these deep holes will be submitted next year.

Fluctuations in surface temperature with time also upsets the upper few meters of the normal temperature gradient in the earth. By measuring these temperature fluctuations and the rate at which the resulting temperature wave is propagated downward, the thermal conductivity of the upper 10-15 m of rock surrounding the well can be calculated. We will time the 20 temperature variation measurements so that we can determine the daily, monthly and yearly temperature fluctuations. The resulting thermal conductivity values will then be compared to the conductivity values determined in the laboratory.

The two to four wells we choose for repeated temperature measurement will be those which have the highest temperatures. These wells will undoubtedly be close to hot rock -- perhaps a relatively recent intrusion body. Repeated temperature measurements will allow us to determine if there is any change in this heat source, such as for example, an injection of new magma. Because of the low thermal conductivity of rock, such a change in heat source would not, under normal circumstances, be detected in one year, unless the heat source was very close to the well. However, because of the high permeability and movement of groundwater in the island, the temperature wave resulting from a new injection of magma will be transmitted to the well site much more rapidly.

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Task 2.5  
Seismic Studies

Investigators: A.S. Furumoto and W. Suyenaga

The seismic studies will consist of the following:

1. Seismicity study of microearthquakes including the use of borehole seismometers
2. Marine seismic refraction and reflection surveys over the seaward extension of rift zones
3. Processing and analysis of seismic data obtained during June-September 1974.

1. Microearthquakes will be continued to be monitored in the Puna area during the calendar year. Seasonal variation of earthquakes has been observed in other seismic areas, and perhaps Puna area may also show such variation. However if microearthquakes are associated with geothermal sources, there should be a level of seismicity irrespective of seasons.

To increase the capability of detection, seismometers will be placed in holes left open by the drilling program. For this purpose, new geophones are requested in the budget. At first we propose to lower geophones only, but if this is unsatisfactory, we will have to fabricate a down hole package to include seismic amplifiers and batteries.

2. The southwest rift zone of Mauna Loa has a 300 m vertical scarp on land but 4 miles at sea the research vessel VALDIVIA found a 1900 m vertical scarp as the seaward extension of the same rift. Infrared scanning surveys showed that this particular rift has thermal anomalies. Hence a thorough survey of the rift

is necessary to understand tectonics. The survey will be done by the University of Hawaii research vessel KANA KEOKI. The vessel is equipped to do routinely magnetic surveys, gravity surveys, seismic reflection profiling, single ship seismic refraction by sonobuoys, bathythermograph measurements. All of these will be done over the rift.

Since the ship will be in the region, the extensions of the rift zones of Kilauea will also be surveyed.

Funds for ship time of the KANA KEOKI is sought by a separate NSF grant for ship operations. Sixteen days of ship time are needed for this survey.

3. During June to August 1974, a large amount of data on seismic noise survey and microearthquake monitoring will be gathered. In the geophysics overview, the seismic noise survey was given as an example of how many times, longer data processing takes than field work. Hence, the main part of this task will be data processing and interpretation.

For the microearthquake monitoring, a computer program to locate epicenters is being prepared. The program is a slight modification of HYP071 which was developed by staff members of the U.S. Geological Survey.

Task 2.6  
Geochemical Surveys

Pow-Foong Fan

Studies of the stable isotopes of oxygen and hydrogen in groundwater have been found to be useful in the discovery and evaluation of geothermal systems. In addition, studies of sodium, potassium and calcium concentrations in the groundwater have recently been shown to be another useful geochemical tool in investigating geothermal systems (Coplen, 1973; Fournier and Truesdell, 1973).

Oxygen and deuterium isotope studies of 10 wells and 2 warm-water springs have been made in the Puna Rift System of Kilauea Volcano, island of Hawaii. Temperature and chemical measurements have also been analyzed in an effort to determine the thermal history of the groundwater. Results show a positive correlation between  $\delta O^{18}$  and temperature, especially where the Puna waters are compared with other Hawaiian waters. The  $O^{18}$  enrichment can be interpreted as water-rock exchange at geothermal temperatures ( $>150^{\circ}C$ ) or contamination of fresh waters by seawater advection since the Puna waters showings the greatest enrichment also have high salinity. Both processes probably occur there and either can result from thermal anomalies at depth.

We propose (1) to make a detailed literature study of the geochemistry of the Hawaiian Islands, especially the geochemistry of Kilauea Volcano; (2) to make chemical and isotopic studies of the groundwater; and (3) to determine mineralogical and chemical compositional change that may have resulted from hydrothermal alteration processes.

We plan to sample water from wells, springs, local precipitation, and geochemical fluids in the Puna, Great Crack and South Point of the island of Hawaii. Special efforts will concentrate on study of water and rock samples from the proposed 8 shallow holes from Puna target areas. We hope our data will assist the

site selection of the deep holes that will eventually be drilled on the island of Hawaii.

The alteration products, hematite, amorphous iron, opal and kaoline were formed by reactions of gases and wall-rock at Sulphur Bank, near the Volcano House on the north rim of Kilauea Caldera. Similar deposits are present in areas along the southeastern boundary cliff of Kilauea Caldera and the Southwest Rift Zone of Mauna Loa near Sulphur Cone. Hydrothermal alteration products that are characterized by chlorite-quartz assemblages are found in the Iao Valley of West Maui and Keolu Hills of windward Oahu. Zeolites and calcite are present 4,000 feet at depth of Keller's well at Kilauea. The mineral assemblages of hydrothermal alteration vary from place to place. More detailed mineralogical and chemical studies are needed to understand the influences of the gas-liquid-solid interface reaction between hydrothermal fluid, groundwater, and wall-rock. Opal, quartz, calcite, kaoline and other minerals resulted from hydrothermal alteration would be deposited in the pores of the rocks and possibly form an impermeable dome around the self-sealing steam reservoir. The identification and understanding of different types of Hawaiian hydrothermal alteration products would be useful background information prior to the drilling project.



## Task 2.7

### Hydrology

R.W. Buddemeier, P. M. Kroopnick  
and L.S. Lau

Hydrologic knowledge is essential to the exploration for, evaluation and exploitation of geothermal power resources. A combination of physical, chemical and isotope hydrologic techniques are required to describe the rates and pathways of groundwater and seawater supply to heat sources, the size and characteristics of geothermal fluid reservoirs, the rates and pathways of escape of geothermally altered or juvenile waters, and the effects on non-geothermal water resources of drilling, energy production, etc.

Hydrologic studies including chemical,  $^{14}\text{C}$ ,  $^{13}\text{C}/^{12}\text{C}$  and  $^3\text{H}$  analyses have been successfully used to characterize the dynamics of groundwater systems in non-geothermal areas of Hawaii<sup>1, 2</sup>. In addition, the use of  $^{18}\text{O}/^{16}\text{O}$  and  $^2\text{H}/^1\text{H}$  ratios in combination with these other techniques strengthens regional hydrology investigations<sup>3</sup>, permits identification and has demonstrated potential for exploration<sup>5</sup> and for assessment of reserves and alterations in producing geothermal energy systems<sup>6</sup>.

Because of the broad and multifaceted applicability of hydrologic and related isotope geochemical data, this task is envisioned as continuing in various forms throughout the remainder of the project. In year 02, the major goals are: (1) assembly, integration with the geochemical reconnaissance data and interpretation of all available hydrologic data on the regions of potential geothermal interest; and (2) measurement of the temperature, chemical composition, and hydrogen and oxygen isotope content of rainwater, well water and natural groundwater in the regions of interest. The analytical program will be initiated promptly at the

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(See footnotes at the end of this task description.)

beginning of the project year (all necessary facilities are on hand and operational in HIG and WRRRC), and will be designed to assist in characterizing regional hydrologic regimes, to refine the identification of geothermal waters and their sources and pathways, to establish baseline data necessary for the interpretation of pump tests and production data in subsequent phases of the project, and to assist in test well siting decision.

Investigations will concentrate on the Puna district, but not to the exclusion of basic characterization of all other areas which appear to offer significant potential for geothermal energy.

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## Task 2.8

### Physical Properties of Rocks

M. H. Manghnani

In geophysical exploration for potential geothermal energy, seismic velocity ( $V_p$  or  $V_s$ ) is one of the most direct and useful parameters. Seismic velocity in a rock depends upon density, porosity, composition (or, mean atomic weight), pressure and temperature at depth. The effects of temperature on velocity in vesicular basalts at modest pressures (1-5 kbar) are not known; hence, a realistic interpretation of subsurface temperature distribution, a useful indicator of successful exploitation of geothermal energy, cannot be made from the observed seismic data.

Recently, it has been shown that both  $V_p$  and  $V_s$  in rock and rock-forming minerals having the same mean atomic weight, are linearly related to thermal conductivity<sup>1,2,3</sup>. Such a relation, if established for the Hawaiian basaltic rocks, would be most useful for interpreting, from seismic velocities, subsurface thermal conductivity and hence the temperatures beneath the potential areas. A knowledge of thermal conductivity of basalts as function of density, porosity, fluid content, and temperature is also needed for the interpretation of heat flow measurements.

That the velocity is also in some manner related to the electrical resistivity of rocks was recently noted.<sup>4</sup> Besides this, there is a real need to know the effect of porosity, fluid content (amount and kind of fluid), temperature, and modest pressure on the electrical resistivity of basaltic rocks in order to interpret the field electrical resistivity measurements.

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(See footnotes at the end of this task description.)

We propose here a twofold program:

1. To undertake laboratory studies for investigating the relationships among geophysical parameters, such as velocity ( $V_p$  and  $V_s$ ), thermal conductivity, and electrical resistivity of basaltic rocks, having various density, porosity and fluid content under the pressure and temperature environments compatible with depth to a few kilometers of interest (i.e. to 300°C and 5 kbar). The results will enable us to understand the effects of porosity on the physical properties, and the relationships among various physical parameters of basaltic rocks.
2. To use these relationships in the interpretation of observed geophysical data for locating the dense subsurface rock and the "optimum" heat source.

The subject basaltic rocks will be collected from the volcanic areas of geothermal importance. The pulse transmission method of  $V_p$  and  $V_s$  measurements<sup>5</sup> will be used. For studying the electrical resistivity of basaltic rocks under various temperature and pressure environments the technique described by Brace et al. (1965)<sup>6</sup> will be followed. For the thermal conductivity measurements, the line-source transient method<sup>7,8</sup>, will be used. Most of the necessary equipment for carrying out the proposed laboratory measurements is available. However, some electronic equipment is needed for making the thermal conductivity and electrical resistivity measurements of rock specimens.

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## CURRENT RESEARCH SUPPORT FOR PRINCIPAL INVESTIGATOR

The following is a listing of the extramurally-funded projects for Augustine Furumoto, Principal Investigator of the Geophysical Program.

1. Oceanographic Investigations  
Office of Naval Research, Project NR-083-603
2. An Engineering Feasibility Study of an Ionospheric Technique  
to Improve Tsunami Warning Systems  
National Science Foundation, Grant GI-34973

VITAE AND BIBLIOGRAPHIES FOR  
GEOPHYSICAL PROGRAM



Robert W. Buddemeier

Born: 24 February 1939, Chicago, Illinois

Marital Status: Married, 3 children

Education

University of Illinois (Urbana), B.S.

Chemistry (Departmental Distinction and High College Honors), 1955-58

University of California (Berkeley) Chemistry, 1958-59

University of Washington (Seattle), Ph.D. Chemistry, 1963-69

Professional Experiences

1955-58 Univ. of Illinois, Undergraduate Lab. Assist.

1958 Technical Chemist, E.I. DuPont Co.

1958-59 NSF Fellow, Univ. of California

1959-62 US Army Security Agency

1962-65 Mass Spectrometrists, Univ. of Wash.

1965-66 Shell Oil Co. Fellow, Univ. of Wash.

1966-69 NASA Predoctoral Trainee, Univ. of Wash.

1969-72 Assist. Professor of Chemistry, Univ. of Hawaii

1972- Pres. Assist. Prof. of Oceanography, Univ. of Hawaii

1969- Pres. Staff Member, Hawaii Institute of Geophysics

Society Memberships

American Geophysical Union

American Assoc. for the Advancement of Science

Western Society of Naturalists

Publications

(with P.E. Yankwich) "Large Reverse Carbon Isotope Effect," J. Chem. Phys., 30(3), 861-862, 1959.

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- (with D.W. Knutson, S.V. Smith) "Coral Chronometers: Seasonal Growth Bands in Contemporary Hermatypic Corals," Science, 144, 270-2, 1972.
- (with T.H. Hufen) "Hawaii Institute of Geophysics Radiocarbon Dates I," Radiocarbon, 15(1), 68-74, 1973.
- (with D.W. Knutson) "Distribution of Radio-nuclides in Reef Corals: Opportunity for Data Retrieval and Study of Effects," p. 734-745 in Radioactive Contamination of the Marine Environment, IAEA, Vienna, 1973.
- (with H.S. Okamoto, T.H. Hufen, and D.C. Hurd) "Effects of Solution and Exchange on the Radiocarbon Dating of Sediments and Natural Waters," P. 297-309, in Proceedings 8th Internat'l Radiocarbon Dating Conf., Roy. Soc. N.Z., Wellington, 1972.
- (with T.H. Hufen and L.S. Lau) "Isotopic and Chemical Characteristics of High Level Dike Confined Groundwater on Oahu, Hawaii," (abs) EOS, Trans. Amer. Geophys. Union, 53(11), 982, 1972.
- (with T.H. Hufen and L.S. Lau) "Isotopic and Chemical Characteristics of High Level Groundwater on Oahu, Hawaii," Water Res. Research, 10, 365-370, 1974.
- (with J.E. Maragos, and D.W. Knutson) "Radiographic Studies of Reef Coral Exoskeletons: Rates and Patterns of Coral Growth," J. of Experimental Marine Biology and Ecology 14, 179-200, 1974.
- "Environmental Controls over Annual and Lunar Monthly Cycles in Hermatypic Coral Calcification," in Proceedings 2nd Internat'l Coral Reef Symp. (in press), 1973.
- (with T.H. Hufen and L.S. Lau) "Radiocarbon, Carbon-13 and Tritium in Water Samples from Basaltic Aquifers and Carbonate Aquifers on the Island of Oahu, Hawaii," in Proceedings, Symposium on Isotope Techniques in Groundwater Hydrology, IAEA, Vienna, (in press) 1974.

David Epp

Academic Training:

Univ. of Kansas	Jan. 1963	B.S. in Geol. Engr.
Univ. of Kansas	June- July 1963	Graduate Work
Univ. of Hawaii	Sept. 1971-present	Graduate Work
Univ. of Hawaii	May 1973	M.S. in Geology and Geophysics

Professional Experience:

Feb-Dec 1964	Lamont Geological Obs., working with the heat flow prog.
Aug 65-July 71	Lamont Geol. Obs., working with the heat flow prog.
Sept. 1971 - present	Graduate Asst., Hawaii Inst. of Geophys., Univ. of Hawaii, working with the heat flow prog.

Shipboard Experience:

Feb-Dec 1964	R.V. VEMA
Nov -Dec 65	U.S.N.S. ELTANIN
Feb 66	R.V. VEMA
June-Aug 66	R.V. CONRAD
Feb 67	"
Aug-Oct 67	Chief Scientist, R.V. CONRAD
July-Aug 68	Chief Scientist, R.V. VEMA
May-June 1969	R.V. SEIFU MARU
Jan-Feb 71	R.V. VEMA
Dec 71 - Jan 72	R.V. KANA KEOKI

Society Membership:

American Geophys. Union  
American Assoc. for the Advancement of Science

Publications:

1970

(with P.J. Grim and M.G. Langseth, Jr.) Heat flow in the Caribbean and Gulf of Mexico, J. Geophys. Res., 75, 5655-5669.  
(with T. Watanabe, S. Uyeda, M.G. Langseth, Jr.) Heat flow in the Philippine Sea, Tectonophysics, 10, 205-224.  
(with M. Yasui, K. Nagasaka, and T. Kishii) Terrestrial heat flow in the seas around the Nansei Shoto (Ryukyu Islands), Tectonophysics, 10, 225-234.

POW-FOONG FAN

Associate Professor of Geology

Birth Date: September 4, 1933  
Palembang, Indonesia

Education:

1955	Wheaton College, Illinois, B.S.
1963	University of California, Los Angeles, M.A.
1965	University of California, Los Angeles, Ph. D.

Experience:

1955	Summer Geologist, Wah Chang Mining Co., Bishop, California
1960-1963	Teaching assistant, Dept. of Geology, University of California, Los Angeles
1964-1965	Consultant (Mineralogy), Space General, El Monte, California
1965-1970	Assistant Geophysicist, Hawaii Institute of Geophysics, University of Hawaii
1966-1970	Assistant Professor, Department of Geosciences, University of Hawaii
1970 (summer)	Visiting Professor of Geology, Department of Geology, University of California, Santa Barbara, California
1970	Associate Geophysicist, Hawaii Institute of Geophysics, University of Hawaii
1970	Associate Professor, Department of Geosciences, University of Hawaii
1971 (summer)	Visiting Professor of Geology, Department of Geological Sciences, University of California, Santa Barbara, California
1971-1972	Associate Research Geologist, Institute of Geophysics and Planetary Physics, University of California, Riverside, California
1972- Present	Associate Professor of Geology, Hawaii Institute of Geophysics, University of Hawaii

PRINCIPAL PUBLICATIONS

Geological periodicals of mainland China. Economic Geology, v. 56, pp. 786-789 (1961).

Morris, W.J., and Pow-Foong Fan, Abrasion effects on arkose mixtures, J. Sedimentary Petrology, v. 32, pp. 226-230 (1962).

Abstractor for Chemical Abstracts. Abstracts of over 200 articles on geology, geochemistry and mineralogy from Communist China (1959-1963).

Recent silts from Santa Clara River drainage basin, California: A mineralogical investigation of their origin and evolution. University of California at Los Angeles doctoral dissertation, Ann Arbor, Mich., University Microfilms, Inc., 159 pp. (1965).

Fan, Pow-Foong, and S.W. Pottratz, Carbonate mineralogy of Hawaiian beach sands (abstr.), Geol. Soc. Am. Ann. Mtg., p. 36A (1966).

Recent silts in the Santa Clara River drainage Basin, South California: A mineralogical investigation of their origin and evolution (abstr.), Geol. Soc. Am. Spec. Paper No. 101, pp. 65-66 (1968).

Fan, Pow-Foong, and R.R. Grunwald, Mineral assemblages of recent Hawaiian marine sediments (abstr.), Geol. Soc. Am. Spec. Paper No. 115, p. 63 (1968).

Geological Contributions from China: Problems of Chinese Geotectonics. Problems of Structural Geology. Characteristics of the Geological Structure of the Mesozoic and Cenozoic in Northern and Southern China. Science Press. (1965-1966). (Book Review). Science, v. 162, pp. 888-889 (1968).

Woollard, George P., and Pow-Foong Fan, The relation of gravity anomalies to geology of East and Southeast Asia (abstr.), Geol. Soc. Am. Spec. Paper No. 121, pp. 328-329 (1968).

Fan, Pow-Foong, and W.C. Burnett, Sedimentation in Estuarine pollution in the State of Hawaii. Part II: Kaneohe Bay study, Section A, 46 pp. University of Hawaii Water Resources Res. Center Tech. Report No. 31 (1970).

Clay mineralogy and geochronology in Semi-Annual Progress Report July 1-Dec. 31, 1969 Project No. NR083 603, pp. 45-47, Hawaii Institute of Geophysics Report 70-4, 49 pp. (1970).

Morgenstein, M., and Pow-Foong Fan, The development and composition of sedimentary manganese in the Kauai Channel, Hawaii, in Annual Progress Report Contract N00014-70-A-0016-0001 January 1, 1970-July 30, 1970, pp. 70-72, Hawaii Institute of Geophysics Report 70-27, 75 pp. (1970).

Deep-sea sediment cores from the South Central Pacific Basin (abstr.), Geol. Am. Annual Meeting, Cordilleran Section, pp. 117-118 (1971).

Fan, Pow-Foong, and R.R. Grunwald, Sediment distribution in the Hawaiian Archipelago, Pacific Science, v. 25, pp. 484-487 (1971).

Clay mineral assemblages in Hawaiian marine sediments (abstr.), Program and Abstracts, 20th Clay Minerals Conf., p. 40 (1971).

Mineralogy of coastal and shallow-water sediments of Hawaii (abstr.), Proc. 2nd Coastal and Shallow Water Research Conf., p. 64 (1971).

Fan, Pow-Foong and J.S. Vawter, Disposal patterns of clay minerals from a transverse range into an ocean basin (abstr.), EOS Trans. Am. Geophy. Union, v. 52, p. 830 (1971).

Fan, Pow-Foong, J. Southworth and M. Morgenstein, Analysis of cores taken by USNS SANDS Sea Spider Site pp. G1-36. In Oceanographic observations for acoustical determination in the Pacific Ocean north of Hawaii, May 1969 through October 1969, Hawaii Institute of Geophysics Report HIG-71-11 (1971).

Geology of mainland China, in Encyclopedia of World Geology, Rhodes W. Fairbridge, Ed. Reinhold Pub. Corp., New York.

Mineralogy of some Hawaii coastal and marine carbonates (abstr.), AAPG\_SEPM Ann. Mtg. (1972).

Fan, Pow-Foong and I. Zemmels, X-ray mineralogy study-Leg 12. In Laughton, A.S., et al.; Initial Report of the Deep Sea Drilling Project, v. XII, U.S. Government Printing Office, Washington (1972), pp. 1127-2254.

Fan, Pow-Foong, and R.W. Rex, X-ray mineralogy study-Leg 14. In Hayes, D.E. et al., Initial Report of the Deep-sea Drilling Project, Vol. XIV, U.S. Government Printing Office, Washington (1972), pp. 677-726.

Fan, Pow-Foong, and R.W. Rex, X-ray mineralogy study-Leg 15. In Edgar, N.T., et al., Initial Report of the Deep-sea Drilling Project, Vol. XV, U.S. Government Printing Office, Washington (1972).

Fan, Pow-Foong, and R.W. Rex, Mineralogy of Cretaceous to Holocene deep-sea clays and clay minerals from the Atlantic and Pacific Oceans (abstr.) Program and Abstracts, 21st Clay Minerals Conference (1972).

Fan, Pow-Foong, and R.W. Rex, Mineralogy of deep-sea sediment cores from Atlantic and Pacific Oceans (abstr.), Geol. Soc. Am. Annual Meeting (1972).

Augustine S. Furumoto

Present Position      Professor of Geophysics and Seismologist  
University of Hawaii

Education      Ph.D. Geophysics, St. Louis Univ. (1961)  
M.S. Geophysics, Univ. of Tokyo (1955)  
B.S. Education, Univ. of Dayton (1949)

Past Employment

1949-53      High school teacher, Hawaii  
1953-55      Fulbright Grant, Graduate Student, Univ. of Tokyo, Japan  
1955-56      High School Teacher, Hawaii  
1956-57      Grad. Studies, Theology and philosophy, Marianist Institute  
                 of Studies, Glencoe, Missouri  
1957-61      Grad. Student, St. Louis Univ.  
1958-61      National Science Foundation, Pre-doctoral Fellow  
1960-61      Teaching Assist. St. Louis Univ.  
1960 Summer      National Science Foundation, Summer Seminar Grant, Woods Hole  
                 Oceanographic Institution  
1961 Summer      Research Assist., Woods Hole Ocean. Institute  
1961-67      Assist. Professor, Univ. of Hawaii  
1967-71      Associate Professor, Univ. of Hawaii  
1971-present      Professor, Univ. of Hawaii

Relevant Publications since 1965

- "Seismic Refraction Surveys Along the Hawaiian Ridge, Kauai to Midway Island,"  
(with Campbell and Hussong), Bull. Seism. Soc. Am., 61, 1, 1971, pp. 147-166.
- "Seismic Studies of Sub-surface Structure in the Ewa Coastal Plain, Oahu, Hawaii,"  
(with Campbell and Hussong), Pacific Science, 24, 4, pp. 526-542, 1970.
- "Crustal and Upper Mantle Structure of the Solomon Islands as Revealed by Seismic  
Refraction Survey of November-December, 1966 (with Hussong, Campbell, Sutton,  
Malahoff, Rose and Woollard). Pac. Sci., 24, no. 3, pp. 315-332, 1970.
- "Seismic Refraction Study of the Internal Structure of a Volcanic Cinder Cone,"  
The Crust and Upper Mantle of the Pacific Area, Monograph 12, American Geophys.  
Union, pp. 112-121, 1968.
- "Variation in the Thickness of the Crust in the Hawaiian Archipelago," (with  
Woollard, Campbell and Hussong), The Crust and Upper Mantle of the Pacific  
Area, Monograph 12, Amer. Geophys. Union, pp. 94-111, 1968.

- "A Seismic Refraction Study of the Koolau Volcanic Plug," (with Adams), Pac. Sci. 19, no. 3, pp. 296-305, 1965.
- "Seismic Refraction Studies of the Crustal Structure of the Hawaiian Archipelago," (with Woollard), Pacific Science, 19, no.3, pp. 306-314, 1965.
- "The Structure of Koolau Volcano From Seismic Refraction Studies," (with Thompson and Woollard), Pacific Science, 19, no. 3, pp. 306-314, 1965.
- "Ionospheric Recordings of Rayleigh Waves for Source Mechanism," Tsunamis in the Pacific Ocean, Proceedings of the Internat'l Symp. on Tsunamis and Tsunami Research, W.M. Adams, Ed., East-West Center Press, Honolulu, Hawaii, pp. 119-133, 1970.
- "Fossil Ice in Hawaii?", (with Woodcock and Woollard), Nature, p. 226, 873, 1970.
- "Features of Tsunamigenic Earthquakes," (with Adams), Tsunamis in the Pacific Ocean, Proceedings of the Internat'l Symp. on Tsunamis and Tsunami Research, W.M. Adams, Ed., East-West Center Press, Honolulu, Hi., pp. 57-68, 1970.
- "Acoustic Coupling into the Ionosphere From Seismic Waves of the Earthquake at Kuril Island on August 11, 1969," (with Weaver, Yuen, and Pross), Nature, 226, pp. 1239-1241, 1970.
- "Continuous Traveling Coupling Between Seismic Waves and the Ionosphere Evident in May, 1968 Japan Earthquake Data," (with Yuen, Weaver, and Suzuki), J. of Geophys. Research, 74, pp. 2256-2264, 1969.
- "Source Mechanism of the Alaska Earthquakes and Tsunami of March 27, 1964, Part II, Rayleigh Waves," Pacific Science, 21, no. 3, pp. 311-316, 1967.
- "Seismicity of Hawaii, Part I, Frequency-Energy Distribution of Earthquakes," Bull. Seism. Soc. Am., 56, no. 1, pp. 1-12, 1966.
- "A Gravity Survey of the Island of Kahoolawe, Hawaii," Pac. Sci., 19, no. 3, 1965.
- "Field Survey of the Tsunamis of March 28, 1964 in Alaska, and Conclusions as to the Origin of the Major Tsunami," (with Berg, Cox, Kajiura, Kawsumi, and Shima), Hawaii Institute of Geophysics, Rept. 70-2, 1970.
- (with G. Taoka and A.L. Chiu) Natural Periods of a Tall Shear Wall Building, Proceedings of 5th World Conference Earthquake Engineering, Rome 1973.
- (with W.A. Wiebenga, J.P. Webb and G.H. Sutton) Crustal Structure of the Hawaiian Archipelago, Northern Melanesia, and the Central Pacific Basin by Seismic Refraction Methods, Tectonophysics, vol. 20, pp. 153-164.
- (with G. Taoka and A.L. Chiu) Dynamic Properties of Tall Shear Wall Buildings. Journal of Structural Div., American Soc. of Civil Engineers, March 1974.
- "Geophysical Exploration on the Structure of Volcanoes: Two Case Histories." in



Proceedings of the U.S.-Japan Science Seminar on Utilization of Volcano Energy, February 1974. Sandia Laboratories (in press).  
(with W.A. Wiebenga) Possible Use of Rabaul Volcanic Complex as a Source of Energy. Proceedings of the U.S.-Japan Science Seminar on Utilization of Volcano Energy, February 1974, Sandia Laboratories (in press).

A. John Halunen, Jr.

Born: 12 December 1938, Middleboro, Massachusetts

Marital Status: Married, two children

Academic Training:

Boise Junior College, Boise, Idaho	1960	Assoc. Arts
Univ. of Idaho	1965	B.S. in Geology
Univ. of Hawaii	1972	M.S. in Geology and Geophysics
Univ. of Hawaii		(working on Ph.D)

Society Memberships:

- American Geophysical Union
- American Assoc. for the Advancement of Science
- The Society of the Sigma Xi

Professional Experiences:

1962-65

Spent approx. 23 months at the Woods Hole Ocean. Inst. of which 10 months was at sea. Major responsibility during this time was the proper operations of the heat flow prog. on board the institute's res. vessels. Other duties and responsibilities included:

- Maintenance and operation of the 100,000 Joule Sparker syst.
- Piston core sampling
- Dredge sampling
- Oper. and Maint. of free-fall bottom sampling equipment
- Supervision of electronic lab. personnel and data collection
- Operation of underwater camera equipment

Sept. 1965

Asst. in Geophysics, Hawaii Inst. of Geophysics, Univ. of Hawaii.

Took part in many geophysical res. efforts at sea in the Pac. including several trips to the Solomon Islands-New Britain area; the Fiji Plateau; the South Fiji Basin-Lau Basin; the Austral Islands; and more recently the Nazca Plate-Panama Basin.

Served as chief Scientist on the 85-foot R/V TERITU; R/V MAHI; R/V KANAKEOKI

Publications :

(with F.S. Birch) Heat flow measurements in the Atlantic Ocean, Indian Ocean, Mediterranean Sea, and the Red Sea, Journ. Geophys. Res., v.71, p. 583-586.

- (with L.W. Kroenke and G.P. Woollard) 1966, Reflection profiles across Penguin Bank (abst) for Pacific Science Congress.
- (with L.W. Kroenke and G.L. Maynard) 1968, The Structural geology and geomorphology of the Ontong Java Plateau north of the Solomon Islands, Trans. Amer. Geophys. Union, v.49, No.2.
- (with M. Yasui, K. Nagasaki and T. Kishii) Terrestrial heat flow in the Okhotsk Sea - Part II; The Oceanographical Magazine, v.20, no. 1, p. 73-86, 1968.
- (with L.W. Kroenke, G.H. Sutton and G.P. Woollard) 1969, Geophysical reconnaissance of the Darwin Rise (paper was presented at AGU, April 1969).
- (with G.H. Sutton, and J. Michel) 1969, Measure. of ocean's heat flow: Ontong Java Plateau and Darwin Rise areas (paper was presented at AGU, April 1969).
- Heat flow in the Western Equatorial Pacific Ocean; M.S. Thesis, Univ. of Hawaii, 1972.
- (with R.P. Von Herzen) Heat flow in the Western Equatorial Pac. Ocean, J. Geophys. Res., v.78, p. 23, p. 5195-5208, 1973.
- (with R.N. Anderson) 1974, The Implications of Heat Flow for Metallogenesis in the Bauer Deep: Southeastern Equatorial Pacific, note submitted to Nature.

Douglas P. Klein

Present Position: Research Associate, Hawaii Institute of Geophysics  
University of Hawaii

Education: 1963 B.S., Geology, Iowa State University, Ames, Iowa  
1965., General Geophysics, Univ. of Hawaii, Honolulu, Hawaii

Professional experience:

National Science Foundation Traineeship; participated in gravimetric, electromagnetic and geomagnetic surveys (1965-66).

Principle U.S. participant in a cooperative U.S.-Japan research program to study electromagnetic induction on oceanic islands.

Worked at the Tokyo Earthquake Research Institute as visiting research field assistant (1969-70).

Field experience with Askania Geomagnetic Variographs, Sakkisha Recording Fluxgate Magnetometers, LaCoste-Romberg and Worden Gravimeters.

Experience in organizing geophysical surveys (geomagnetic and geoelectric program while at the Univ. of Hawaii, geodetic gravity surveys during military serve).

General knowledge of most gravity, magnetic and land survey instruments and interpretive techniques.

Extensive data processing experience (Fortran IV programming with IBM 360-65 computer).

Publications:

"Spatial Patterns of Time Variations in the Geomagnetic Field on the Hawaiian Islands," J.C. Belshe and D. Klein, U.U.G.G. presentation, 1966.

"Observations of Short-period Geomagnetic Fluctuations of Hawaii," (written in Japanese), with T. Rikitake, T. Yukutake, T. Yoshino, Y. Yamazaki, Proceedings of Symp. on Conductivity Anomaly Studies in Japan, Earthquake Research Institute, Univ. of Tokyo, 1969.

"Observations of Spatial Differences in Geomagnetic Time-Variations on the Island of Hawaii," (with A. Malahoff) Transaction, AGU, 50, 605, 1969.

"Geomagnetic Time-Variations on Hawaii Island and Mantle Electrical Conductivity," Transactions, AGU, 52, 824, 1971.

"Geomagnetic Time-Variations in the Range of .5 to 6 cycles per Hour and Electrical Depth Sounding on the Island of Oahu, Hawaii," M.S. Thesis, Univ. of Hawaii, 1972.

Memberships:

American Geophysical Union

Geology Club

Society of American Military Engineers (student chapter)

Society of Exploration Geophysics

Peter M. Kroopnick

Born: 31 January 1942 in Detroit, Michigan

Marital Status: Married 1968, one child

Education: Wayne State University, 1963, B.S. Chemistry

Univ. of California, Berkeley, Ca., 1965, M.S. Chemistry

Univ. of Ca., San Diego, Ca., 1971, Ph.D. Earth Sciences

Positions: Teaching Asst., Chemistry Dept., Univ. of Ca., Berkely, 1963-64

Res. Asst. Inorganic Materials Res., Div., Lawrence Radiation Lab.

Univ. of Ca., Berkeley, 1964-65

Res. Asst., Scripps Institution of Ocean., Univ. of Ca., San Diego  
1965-68

Westinghouse Fellow, Univ. of Ca., San Diego, 1968-70

Participant, CIRCE Expedition, Central Pacific, 1968

Participant, SCAN Expedition, Eastern Pacific, 1970

Part., GEOSECS 2 Intercalibration Station North Atlantic, 1970

Part., NATO Internat'l Summer Inst. on air-sea interact. , Isle of  
Man, Great Britain, 1970

Asst. Professor of Oceanography, Univ. of Hawaii, Honolulu, Hi.,  
Jan. 1971 - present

Participant, Antipode Expedition, South Pacific, 1971

Chief Scientist, Local water chemistry from the TERITU, 1971

Part., First GEOSECS Summer Inst., Woods Hole, 1971

Asst. Chief Scientist, GEOSECS Atlantic Expedition, Leg 3 (Iceland  
to Barbados), 1972

Part., 2nd GEOSECS Summer Institute, Woods Hole, 1973

Assoc. Scientist, GEOSECS Pacific Expedition, Leg E, 1973

Societies: Alpha Chi Sigma

American Geophysical Union

American Association for the Advancement of Science

Grants in effect:

Geochemical Ocean Sections Prog. (GEOSECS) Isotopic Measurements ( $^{13}\text{C}/^{12}\text{C}$ ;  
 $^{18}\text{O}/^{16}\text{O}$ ; D/H) in Dissolved Inorganic Carbon, Atmospheric  $\text{CO}_2$ , Dissolved  
Oxygen, and Atmospheric Water Vapor, NSF, GX28168, \$33,000, Jan. 1972-  
June 30, 1972, P. Kroopnick, P.I.

Renewal of above NSF P2X0070, \$64,000, 7/1/72 - 12/31/73, P. Kroopnick,  
P.I. Renewal 1/73 - 1/74.

Environmental Isotope Applications to Hawaiian Ground Water (Phase III) OWRR,  
\$25,700. R.W. Buddemeier, P.I., P. Kroopnick, Assoc. Investigator.

Request for Isotope Ratio Mass Spectrometer, NSF, \$46,200, Kroopnick, P.I.  
March 1, 1973.

Investigation of the Nature of Physical and Chemical Processes Active at and  
near the Sediment-water Interface in the Deep Sea, ONR, Task 3, Sept. 72-  
Aug. 1973, Kroopnick, Assoc. Investigator.

Investigation of the Nature of Physical and Chemical Processes Active at and near  
the Sediment-Water Interface in the Deep Sea, ONR, Task 3, 9/73-8/74.  
Kroopnick, co-investigator.

#### Proposals pending or being prepared:

Isotopic and Chemical Evaluation of Hawaiian Ground Water Resources, \$24,000.  
Kroopnick, co-investigator. (fund. anticipated Sept. 1973).

The Deep and Bottom Water Circulation . . . (fund. Aug. 1974) NSF

Investigation of Nitrogen and Carbon . . . (in prep.) ONR

#### Publications:

Carbon 13 measurements on dissolved inorganic carbon at the GEOSEC 1969 Intercalibration Station." J. Geophys. Res., 75, 7668 (1970) With W.G. Deuser, and H. Craig.

"Oxygen 18 variations in dissolved oxygen in the sea." Transactions of the Am. Geophys. Union, 51, 325 (1970). (with H. Craig)

"Geochemical and temperature profiles in equatorial Pacific bottom water." Transactions of the American Geophys. Union, 51, 325 (1970). (with H. Craig, J.G. Sclater, Y. Chung, J.M. Edmond, and R.F. Weiss).

Isotopic composition of molecular oxygen in the atmosphere and the sea." Transact. of the Am. Geophys. Union, 52, 255 (1971). (with H. Craig).

"Atmospheric oxygen: Isotopic composition and solubility fractionation." (with H. Craig), Science, 175, 54, 1972.

"Total CO<sub>2</sub>, <sup>13</sup>C, and dissolved oxygen--<sup>18</sup>O at GEOSEC II in the North Atlantic." Earth and Plan. Sci. Letters, 16, 103-110 (1972), (with R.F. Weiss, H. Craig).

"Carbon 13 measure. on dissolved inorganic carbon and Oxygen 18 measure. on dissolved oxygen at GEOSECS Stations." Transact. of the Am. Geophys. Un., 53, 401 (1972). (with H. Craig).

"The dissolved oxygen-total CO<sub>2</sub> - <sup>13</sup>C sys. the East. Equatorial Pac." Deep Sea Research, in press, v.21.

"<sup>13</sup>C-CO<sub>2</sub> correlations in the atmosphere and in oceanic surface water." Transact. of the Am. Geophys. Un., 55, in press, (1974).

#### Manuscripts under review and in Prep.

<sup>13</sup>C- $\delta$ CO<sub>2</sub> correlations in the atmosphere and Pac. surface waters, submitted to Earth and Plan. Sci. Letters, March 1974.

Oxygen 18 variations in dissolved oxygen in the sea. (with H. Craig).

NAME

L. STEPHEN LAU

PRESENT POSITIONProfessor, Civil Engineering  
Director, Water Resources Research CenterEDUCATIONPh.D., University of California at Berkeley, 1959  
M.S., University of California at Berkeley, 1955  
B.S., University of California at Berkeley, 1953PAST EMPLOYMENT

1971-present	Director, WRRRC, University of Hawaii; Professor, Civil Engineering, University of Hawaii
1967-1971	Associate Director, WRRRC, University of Hawaii; Professor, Civil Engineering, University of Hawaii
1966-1967	Acting Director, WRRRC, University of Hawaii
1965-1966	Visiting Associate Professor, University of California
1964-1965	Director, Pacific Island Sanitary Engineering Program, U.S.P.H.S., University of Hawaii
1960-1964	Ground Water Consultant, Honolulu Board of Water Supply

PRINCIPAL PUBLICATIONS

"Methods of Monitoring Salt Water Encroachment in Hawaii," with C. Lao, presented at the Fifth International Conference International Association of Water Pollution Research, Reconvened Session, Honolulu, Hawaii, August 2-5, 1970.

"Ground-water Resources and Development: Coastal Plain Region, Erh Jen Chi-Kaohsiung, Taiwan," with John F. Mink and Chester Lao, WRRRC Technical Report No. 47, May, 1971, 153 pp.

"Hydrologic Systems in Hawaii," with P.C. Ekern, F.L. Peterson, S. Price, and R. Pulfrey, systems Approach to Hydrology, (Proceedings of the First Bilateral U.S.-Japan Seminar in Hydrology, Honolulu, January 11-17, 1971, pp. 186-201.

"Tritium Measurement of Natural Waters on Oahu, Hawaii: a Preliminary Interpretation (sampling period: July 1969 to June 1970)," May 1973, 39 pp.

PROFESSIONAL SOCIETIESAmerican Society of Civil Engineers  
American Geophysical Union  
Federal Water Pollution Control  
American Water Resources Association



MURLI H. MANGHNANI

Professor of Geophysics

EDUCATION: B.S., Bihar University, 1957  
M.S., and A.I.S.M., Indian School of Mines, 1958  
Ph.D., University of Montana, 1962  
Post-Doctoral Research in Geophysics, University of Wisconsin, 1962-1963

PAST EMPLOYMENT:

1958-1962	Graduate Teaching and Research Assistant, University of Montana
1959 (summer)	Geophysicist, Montana Phosphate Products Company
1962-1963	Post-Doctoral Research Fellow (Geophysics), University of Wisconsin
1964-1969	Assistant Professor of Geosciences, University of Hawaii
1969-1974	Associate Professor of Geophysics, University of Hawaii
1974-Present	Professor of Geophysics, University of Hawaii

CURRENT RESEARCH:

Current research interest lies in the area of pressure and temperature dependences of physical properties (mainly, elastic properties) of rock materials, glasses, and metals. Two research grants have been received from NSF and ONR to investigate the elasticity of silicate glasses and single crystal h.c.p. metals.

AWARDS:

Indian School of Mines Scholastic Awards, 1955-1958  
Society of Exploration Geophysicists Scholarship, 1962  
National Academy of Sciences; National Research Council Senior Post-Doctoral Research Associateship tenable at AFCRL, 1970

PRINCIPAL PUBLICATIONS:

- "Establishment of North-South Gravimetric Calibration Line in India," 1963, J. Geophys. Res., v. 68, pp. 6293-6301. (with G. P. Woollard).
- "Glaucconites: Cation Exchange Capacities and Infrared Spectra, Part I," 1964, Amer. Mineralogist, v. 49, pp. 586-598, (with J. Hower).
- "Glaucconites: Cation Exchange Capacities and Infrared Spectra, Part II," 1964, Amer. Mineralogist, v. 49, pp. 1631-1642, (with J. Hower).
- "Ultrasonic Velocities and Related Elastic Properties of Hawaiian Basaltic Rocks," 1965, Pac. Sci., v. 19, no. 3, pp. 291-295, (with G.P. Woollard).
- "Elastic Wave Velocities in Hawaiian Rocks at Pressures up to 10 Kilobars," 1968, in Leon Knopoff, Charles L. Drake, and Pembroke J. Hart (eds.), The Crust and Upper Mantle of the Pacific Area, Geophys. Mono. no. 12, pp. 501-516, Am. Geophys. Union, Washington, D. C. (with G.P. Woollard).

MURLI H. MANGHNANI (2)

Publications (continued)

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MURLI H. MANGHNANI (3)

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building

Publications:

- (with D.N. Hart) 1970, Confirmation of Sofar-Hydrophone Detection of Submarine Eruptions, J. Geophys. Res., v. 75, no. 11, p. 2144-2147.
- (with R. Johnson) 1969, Submarine Volcanic Eruptions Recently Located in the Pacific by Sofar Hydrophones, J. Geophys. Res., v.74, no. 2, p. 650-664.
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- (R. Johnson) 1968, T-phase Radiators in the Western Aleutians, Bull. Seism. Soc. Am., v. 58, no. 1, p. 1-10.
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- (with Pong, William) 1965, Photoemission from Amorphous and Metallic Selenium in the Vacuum Ultraviolet, J. Opt. Soc. Am., v.55, No. 9, p. 1189-1190.
- (with R. Johnson) 1971, Significance of Spectral Banding in the Hydroacoustic Signals from Submarine Volcanic Eruptions: Myojin 1970, J. Geophys. Res., vol. 77, no. er.

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| 1960-1963 | University of Strasbourg, France, B.S. (Physics)   |
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| 1971-         | University of Hawaii, Assistant Geophysicist                                  |

Publications:

- Elasticity and fabric of dunites, A.G.U. Pacific Northwest Regional Meeting (abstract), 1971 (with N. I. Christensen).
- Elastic moduli and anisotropy of dunite to 10 kbars, J. Geophys. res., 76, 4003-4010, 1971 (with N. I. Christensen).
- Compressional wave velocities in granulites and eclogites to 10 kbars, A.G.U. Fall Annual Meeting (abstract), 1972 (with M. H. Manghnani).
- Compressional- and shear-wave velocities in granulites and eclogites to 10 kbars (accepted for publication, J. Geophys. Res.) 1974 (with M. H. Manghnani and S. P. Clark).
- Garnet granulite as constituent of the lower oceanic crust (in preparation).
- Effect of pressure and temperature on the velocity anisotropy in dunites and single-crystal olivine (in preparation) (with M. H. Manghnani).

## HAWAII GEOTHERMAL PROJECT

### ENGINEERING PROGRAM

#### INTRODUCTION

The principal objectives of the Engineering Program are (1) applied research in problem areas related to the extraction of energy from geothermal resources, and (2) planning and design of environmentally-acceptable geothermal power plants. Research during the past period has been in the areas of (1) studies complementary to and in support of the Geophysics Program, and (2) studies of the economical and technological feasibility of different methods of converting heat energy in a geothermal reservoir to electrical energy. Results of the research effort have been reported in three quarterly progress reports published to date, and the following technical memorandum and reports:

1. Modelling of Hawaiian Geothermal Resources, Technical Report No. 1, January, 1974.
2. Warm water Wells on the Island of Hawaii, Technical Memorandum No. 1, January, 1974.
3. Steady State Free Convection in an Unconfined Geothermal Reservoir, Technical Report No. 2, March 15, 1974, by P. Cheng and K. H. Lau, accepted for publication in the Journal of Geophysical Research.
4. Geothermal Reservoir Engineering: State-of-the-Art, Technical Report No. 3, March 15, 1974, by P. Takahashi, B. Chen, and K. Mashima.
5. Regenerative Vapor Cycle with Isobutane as Working Fluid, Technical Report No. 4, June 10, 1974, by J. Chou, R. Ahluwalia, and E. Woo.
6. Numerical Solutions of Isothermal Pumping and Re-injection, Technical Report No. 5, July 1, 1974, by P. Cheng and C. Wong.
7. Effects of Vertical Heat Sources on Free Convection in a Rectangular Geothermal Reservoir, Technical Report No. 6, July 15, 1974, by K. H. Lau and P. Cheng (in preparation).

A more detailed description of the applied research being proposed for the Engineering Program follows.

## PHASE I PROGRESS REPORT

### TASK 3.1 GEOTHERMAL RESERVOIR ENGINEERING

The geothermal reservoir engineering research team is composed of three sub-task groups: computer modelling, physical modelling, and geothermal well testing and analysis. The three sub-tasks have the goal of predicting the performance of producing geothermal fields. The computer modelling group will use a mathematical model approach, the physical modelling group will scale model a geothermal system, and the testing and analysis group will evaluate existing geothermal and petroleum gas hardware and software techniques with the aim of synthesizing optimal measurement and prediction alternatives.

The organizational plan and personnel responsible for various sub-tasks are depicted in Fig. 3.1-1.

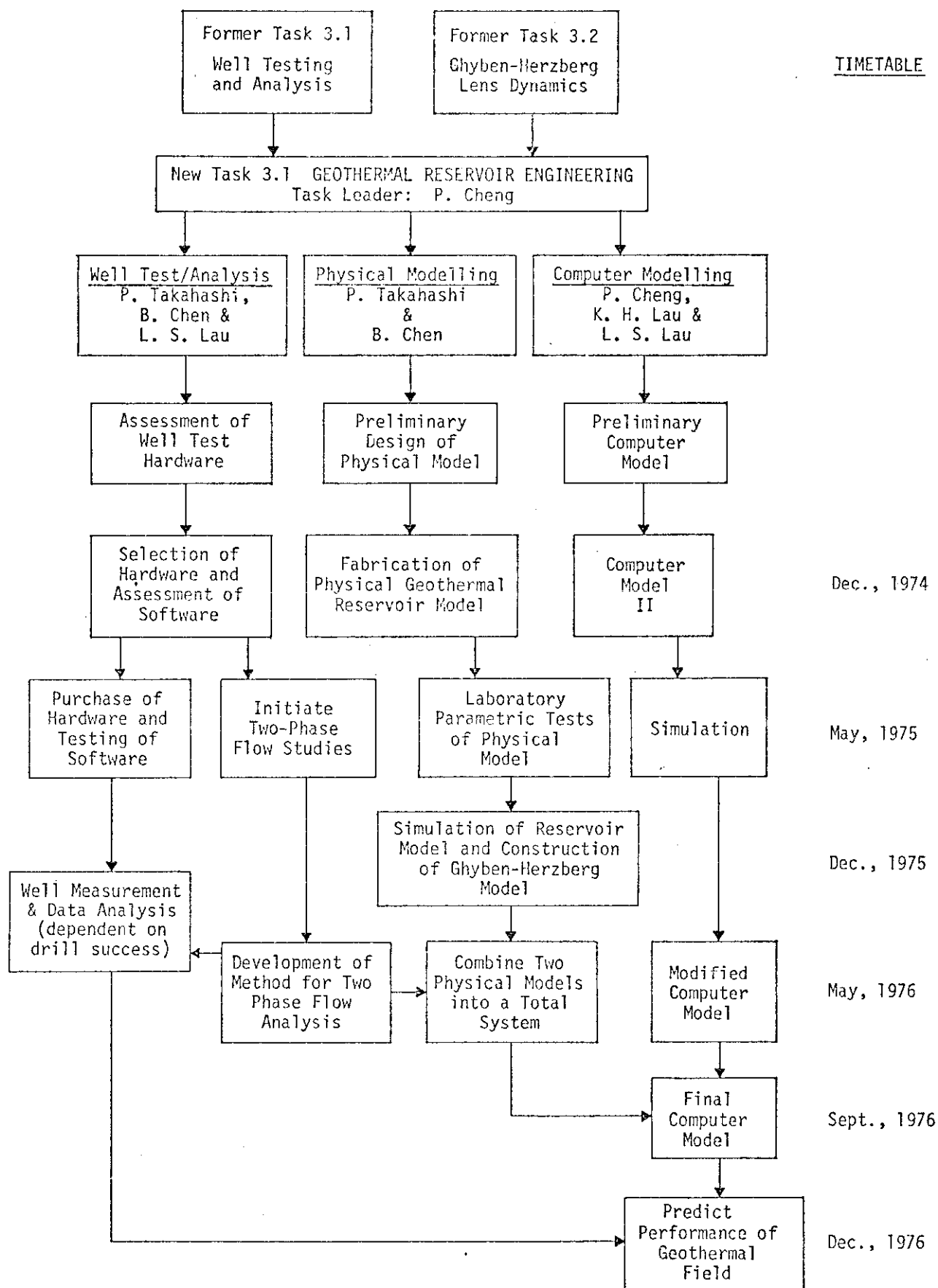


FIG. 3.1-1 ORGANIZATIONAL PLAN FOR THE TASK ON GEOTHERMAL RESERVOIR ENGINEERING



## 1. Numerical Modelling of Geothermal Reservoirs

Investigators: P. Cheng, K. H. Lau, & L. S. Lau

The primary objectives of the numerical modelling are to predict the performance of geothermal wells under different conditions and to study the environmental impact of the geothermal system, especially the stability of the Ghyben-Herzberg lens when perturbed by the extraction of a fluid from a well below the lens. The results of these studies will aid in the selection of a viable well-site. Specific topics to be investigated are:

1. temperature distribution, heat transfer and fluid flow characteristics of geothermal systems on the island of Hawaii,
2. capacity of a geothermal well,
3. expected life span of a geothermal well under different operating and resource conditions,
4. minimum depth required for a geothermal well so that fresh water will not cone downwards to the well bottom as water is pumped out, and
5. effect of fluid recharge on the performance of a geothermal well.

The aforementioned problems have not been reported in the literature. A realistic simulation of Hawaii geothermal reservoirs must take into consideration the anisotropic property of rock formation; the irregular geometry of boundaries; the dynamics of the Ghyben-Herzberg lens; and the effects of pumping, re-injection, and freshwater recharging. Mathematically, the problem is very complicated since it involves the solution of a set of highly non-linear partial differential equations with non-linear boundary conditions at the water table where its position is unknown. The strategy adopted by the numerical simulation group has been to study simplified

situations during the initial phase of the work. These simplified models, which consider different effects one at a time, will aid in a qualitative understanding of the physical processes involved. Furthermore, since the numerical solutions for a more realistic model will probably involve iteration, the results of the simplified models can be used as input data for the first iteration to guarantee convergence of the iteration process. After maturity and expertise have been developed, more realistic models will be considered. The research work will then culminate in the development of a general computer code capable of predicting the performance of a specific geothermal reservoir.

During the first twelve months work has been accomplished in the following three areas:

1. Steady Free Convection in an Unconfined Rectangular Geothermal Reservoir

A parametric study has been completed which investigates the effects of geothermal heating from below on the movement of seawater, the upwelling of water table, and the pressure and temperature distribution in a rectangular two-dimensional geothermal reservoir. A manuscript entitled, "Steady Free Convection in an Unconfined Geothermal Reservoir" by Cheng and Lau, has been accepted for publication in the Journal of Geophysical Research. The following is a brief discussion on the formulation and the numerical results of the problem. (See Technical Report No. 2 for details of the analysis).

The Hawaii geothermal reservoir (Fig. 3.1-1A) is idealized as a two-dimensional porous medium bounded on the bottom by a horizontal impermeable wall and on the vertical sides by the ocean

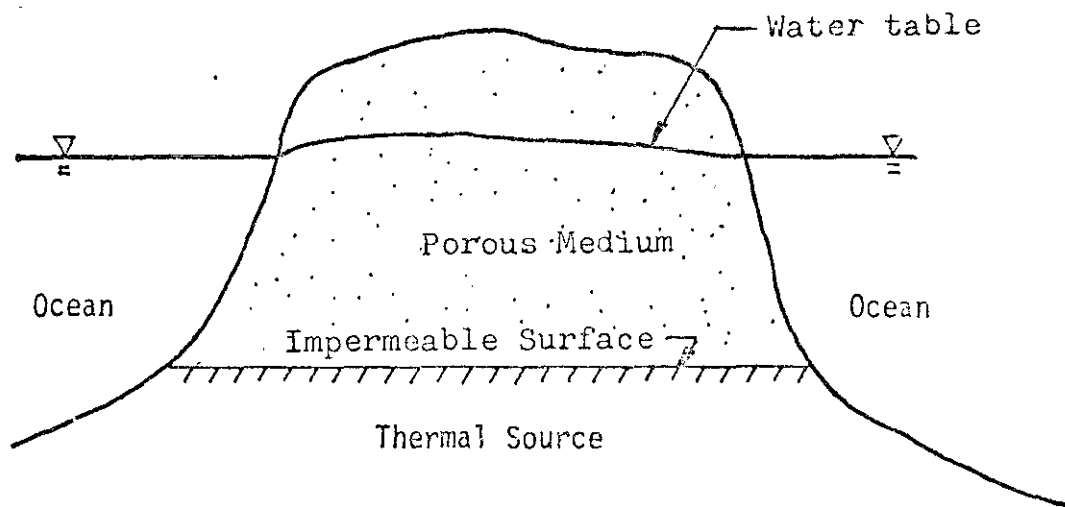


FIG. 3.1-1A UNCONFINED AQUIFER WITH THERMAL SOURCE

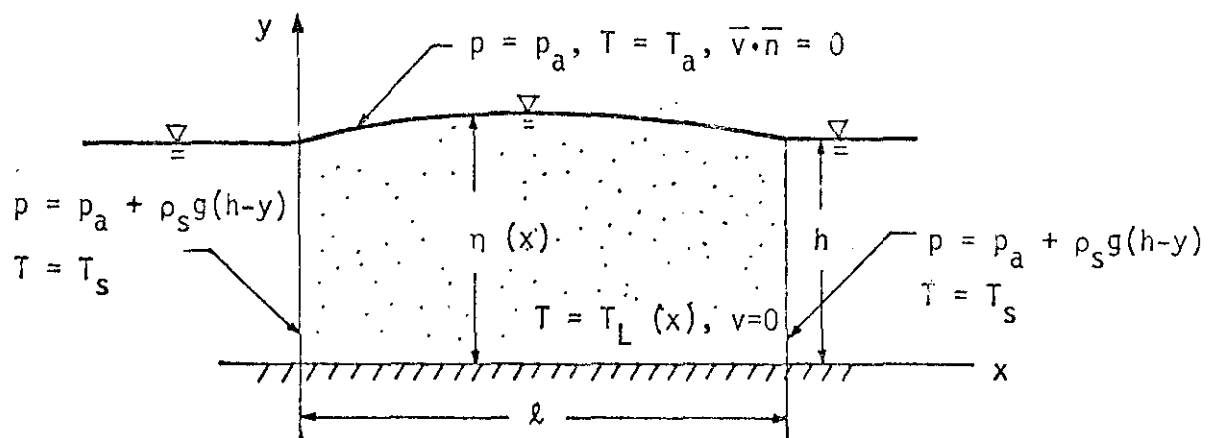


FIG. 3.1-1B RECTANGULAR MODEL OF AQUIFER

(Fig. 3.1-1B). The shape of the water table is not known a priori and must be determined from the solution. To simplify the mathematical formulation of the problem, the following assumptions are made:

- A. The flow field is steady and two-dimensional.
- B. The temperature of the fluid is everywhere below boiling for the pressure at that depth.
- C. The Boussinesq approximation is employed; i.e., density is assumed to be constant except in the buoyancy force term.
- D. There is no accretion at the water table; namely, no rainfall.
- E. Fluid properties such as thermal conductivity, specific heat, kinematic viscosity, and permeability are assumed to be constant.
- F. Ocean is at rest; i.e., the effects of tides are neglected.

With these approximations, the governing equations in terms of dimensionless variables are

$$\frac{\partial^2 P}{\partial X^2} + \frac{\partial^2 P}{\partial Y^2} = \epsilon \frac{\partial \Theta}{\partial Y}, \quad (1)$$

and

$$\frac{\partial^2 \Theta}{\partial X^2} + \frac{\partial^2 \Theta}{\partial Y^2} + D \left[ \frac{\partial P}{\partial X} \frac{\partial \Theta}{\partial X} + \frac{\partial P}{\partial Y} \frac{\partial \Theta}{\partial Y} + [1 - \epsilon \Theta] \frac{\partial \Theta}{\partial Y} \right] = 0, \quad (2)$$

where

$$P \equiv \frac{p - p_a}{\rho_s g h}, \quad \Theta \equiv \frac{T - T_s}{T_c - T_s}, \quad \bar{n} \equiv \frac{\eta}{h}, \quad X \equiv \frac{x}{h}, \quad (3)$$

$$Y \equiv \frac{y}{h}, \quad L \equiv \frac{\lambda}{h}, \quad \epsilon \equiv \beta(T_c - T_s), \text{ and } D \equiv \frac{\rho_s K g h}{\alpha \mu}$$

with  $p$ ,  $T$ ,  $\rho$ , and  $\mu$  denoting the pressure, temperature, density, viscosity;  $\alpha$  and  $K$  denoting the thermal diffusivity and permeability of the medium;  $g$  and  $\eta$  denoting the gravitational acceleration and the height of the water table;  $T_c$  denoting the maximum temperature of the impermeable surface, and the subscript "s" denoting the condition in the ocean;  $\epsilon$  and  $D$  are dimensionless parameters.

The boundary conditions along the ocean are given by

$$P(0, Y) = 1 - Y, \quad (4a)$$

$$P(L, Y) = 1 - Y, \quad (4b)$$

$$\Theta(L, Y) = 0, \quad (5a)$$

$$\Theta(0, Y) = 0. \quad (5b)$$

Along the impermeable surface, the boundary conditions are

$$\frac{\partial P}{\partial Y}(X, 0) = -1 + \epsilon \Theta_L(X), \quad (6a)$$

$$\Theta(X, 0) = \Theta_L(X), \quad (6b)$$

$$\text{where } \Theta_L(X) \equiv \frac{T_L(X) - T_s}{T_c - T_s} \text{ with } T_L(X) \text{ prescribed.} \quad (6c)$$

Along the free surface, the boundary conditions are

$$\frac{\partial \bar{\eta}}{\partial X} \frac{\partial P}{\partial X}(X, \bar{\eta}) - \left[ \frac{\partial P}{\partial Y}(X, \bar{\eta}) + 1 - \epsilon \Theta_a \right] = 0, \quad (7a)$$

$$P(X, \bar{\eta}) = 0, \quad (7b)$$

$$\Theta(X, \bar{\eta}) = \Theta_a, \quad (7c)$$

$$\text{where } \Theta_a \equiv \frac{T_a - T_s}{T_c - T_s} \text{ with } T_a \text{ denoting the atmospheric temperature,}$$

and  $Y = \bar{\eta}(X)$  is the shape of the water table, which is not known a priori, and must be determined from the solution. Since the value of  $\epsilon$  in Eqs. (1-7) is small, the mathematical problem can be simplified based on perturbation method. For this purpose we now assume that dependent variables be expanded in a power series of  $\epsilon$ . Thus we have

$$P(X, Y) = \sum_{m=0}^{\infty} \epsilon^m P_m(X, Y), \quad (8a)$$

$$\Theta(X, Y) = \sum_{m=0}^{\infty} \epsilon^m \Theta_m(X, Y), \quad (8b)$$

$$\eta(X) = 1 + \sum_{m=0}^{\infty} \epsilon^m \eta_m(X), \quad (8c)$$

where  $P_m(X, Y)$ ,  $\Theta_m(X, Y)$  and  $\eta_m(X)$  are perturbation functions to be determined. Substituting Eqs. (8) into Eqs. (1-7), making a Taylor's series expansion on boundary conditions (7), and collecting terms of like power in  $\epsilon$ , we have a set of linear sub-problems.

The governing equations for the zero-order and the first-order problems are respectively the Laplace equation and Poisson equation with nonhomogeneous boundary conditions. In principle they can be solved in closed form by the classical method of separation of variables. However, the numerical evaluation of the resultant expressions in terms of many double and triple Fourier series will be of dubious value because of its slow convergent rate. For this reason we resort to the numerical solution of these linear problems by the finite difference method.

The parameters for the present problem are  $L$  the aspect ratio,  $D$  the discharge number, and  $\epsilon$  the perturbation parameter. Grid values of pressure, temperature, and stream function are computed for  $L=4$ ,  $\epsilon=0.1$  with  $D=50$ , and 500 for the following three temperature distributions of the impermeable surface:

$$(1) \quad \theta_L = \exp \left[ -\left( \frac{X - 2.0}{0.5} \right)^2 \right],$$

with a maximum temperature at  $X=2.0$ ,

$$(2) \quad \theta_L = \exp \left[ -\left(\frac{X - 0.5}{0.5}\right)^2 \right],$$

with a maximum temperature at  $X=0.5$ ,

$$(3) \quad \theta_L = \exp \left[ -\left(\frac{X - 0.5}{0.1}\right)^2 \right],$$

with a maximum temperature at  $X=0.5$ .

Comparison of the numerical results for Cases 1 and 2 will show the effect of the location of heat source whereas the comparison of results for Case 2 (a broad heat source) and Case 3 (a narrow heat source) will show the effect of the size of the heat source.

Fig. 3.1-2 shows the contour of the first order perturbation of stream function,  $\psi_1$ , for Case 1. As is shown in the figure, the fluid particles begin to rise as they approach the point of maximum surface temperature. This is because the density of the fluid becomes smaller as its temperature rises. As the fluid particles rise to a colder region they begin to lose heat and will begin their descending paths when the density becomes the same as that of the surrounding fluid. Fig. 3.1-3 shows the pressure contours for Case 1 with  $\epsilon = 0.1$  and for all values of  $D$ . The fact that the pressure contours are almost horizontal indicates that the pressure in an unconfined geothermal reservoir can be approximated by hydrostatic pressure. The effect of discharge number on temperature contours for Case 1 is shown in Fig. 3.1-4.  $D = 50$  corresponds to the case where heat transfer by conduction is predominant whereas  $D = 500$  corresponds to the case where convection heat transfer cannot be neglected. The effect of discharge number on vertical

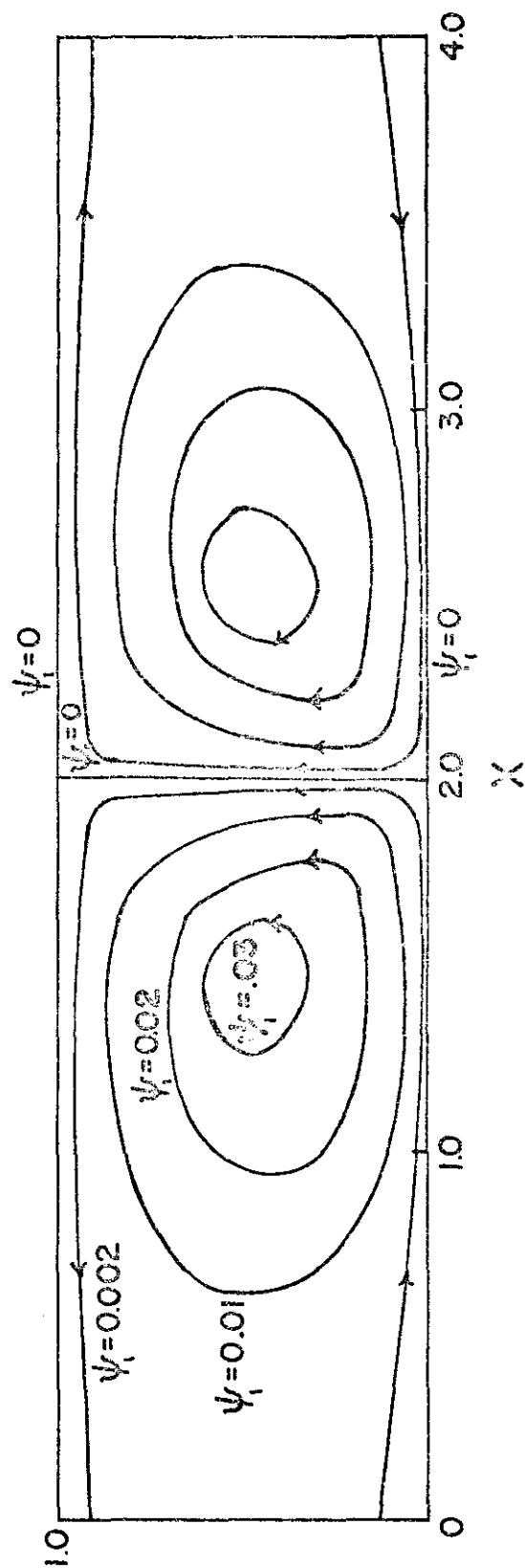


FIG. 3.1-2 CONTOURS OF FIRST-ORDER PERTURBATION FOR STREAM FUNCTION



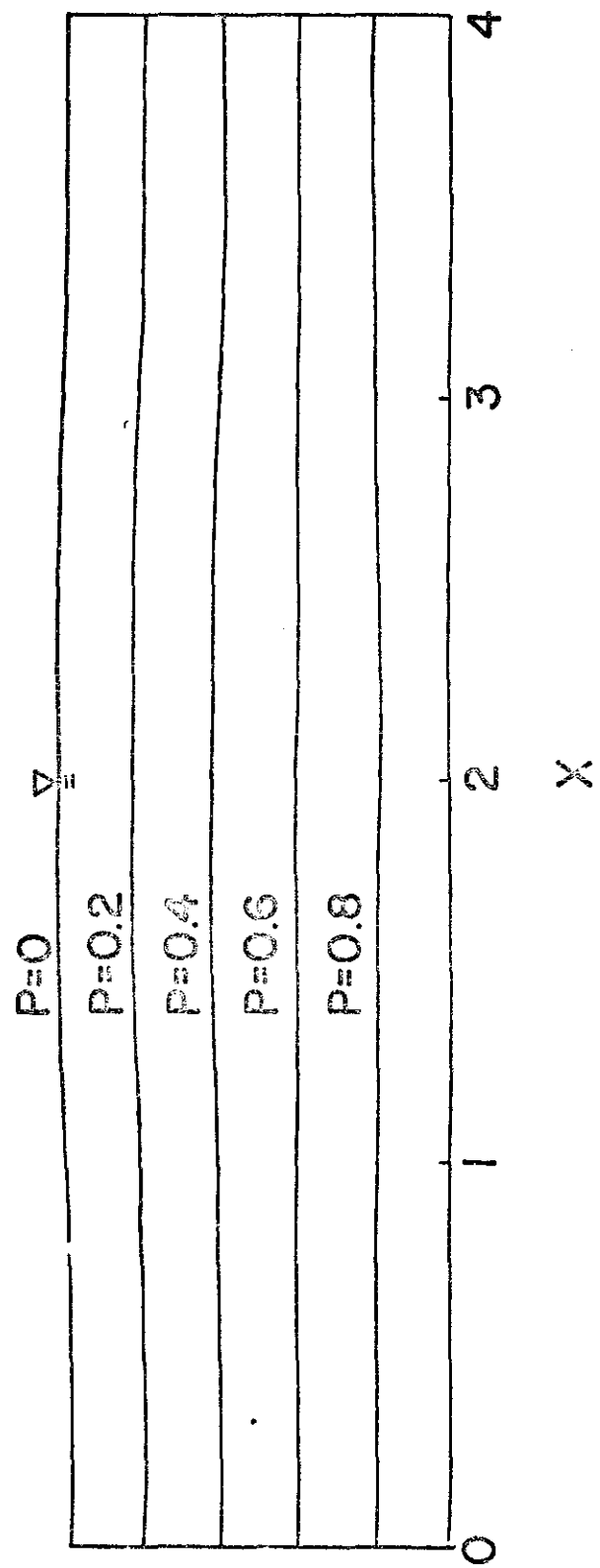


FIG. 3.1-3 PRESSURE CONTOURS FOR CASE 1

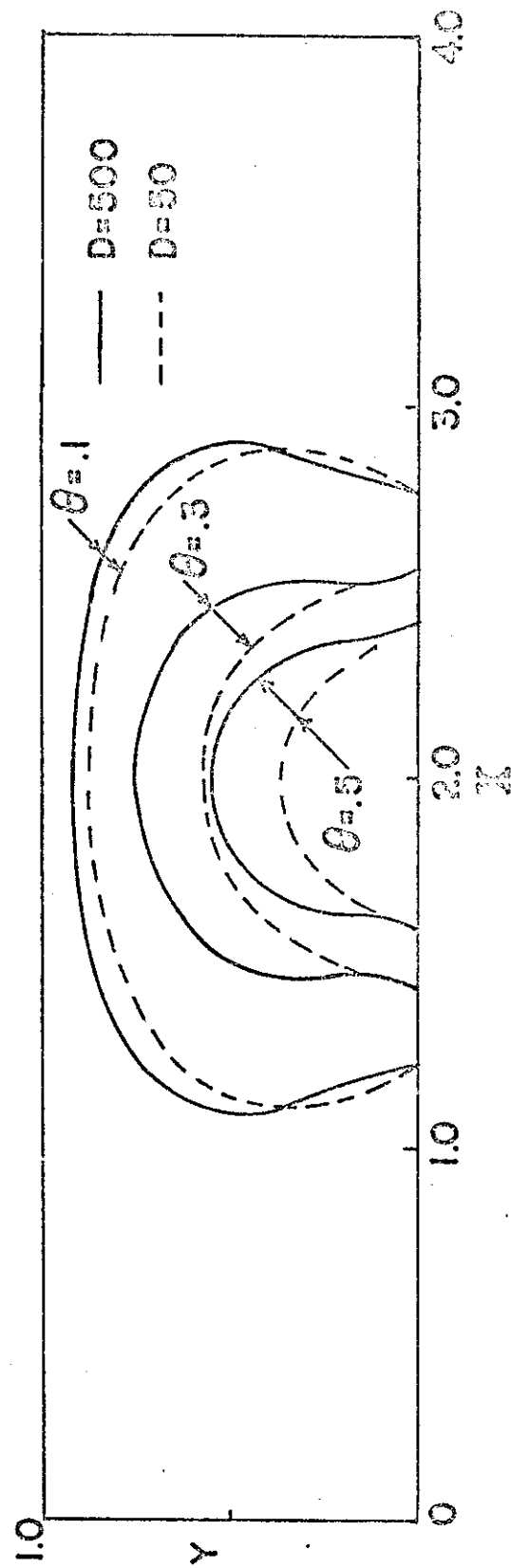


FIG. 3.1-4 EFFECT OF DISCHARGE NUMBER ON TEMPERATURE CONTOURS FOR CASE 1

temperature profiles is shown in Fig. 3.1-5. For locations directly above the point of maximum surface temperature (i.e., at  $X = 2$ ), temperature is higher for higher value of  $D$ . Similar behavior exists in the upper portion of the aquifer. However, in the lower portion of the aquifer, temperature decreases as the value of  $D$  is increased. This is due to the inflow of colder seawater in the lower portion of the aquifer and the outflow of warmer seawater in the upper portion of the aquifer.

Figs. 3.1-6A and 3.1-6B show the effect of location and the size of heat source on  $\eta_1$ , the first order perturbation function for the shape of water table. To the first-order approximation the upwelling of water table is given by  $\epsilon\eta_1$ , and is independent of  $D$ . The amount of upwelling depends on the vertical temperature gradient of the porous medium and the temperature distribution of the impermeable surface. The size and the location of the heat source have a strong influence on the amount of upwelling of water table. The maximum value of  $\eta_1$  is approximately 0.08 at  $X = 2$  for Case 1 (Fig. 3.1-6A). For a heat source near the ocean (Fig. 3.1-6B), it is interesting to note that the location of maximum water table height is not necessarily located directly above the point of maximum temperature of the impermeable surface. In fact, the position of maximum value of  $\eta_1$  moves inland as the size of the heat source is increased.

It is estimated that the value of  $D$  for Hawaii geothermal reservoirs will probably be much higher than  $D = 500$ . Consequently, the numerical results do not really correspond to a realistic situation. However, since temperature distribution increases as

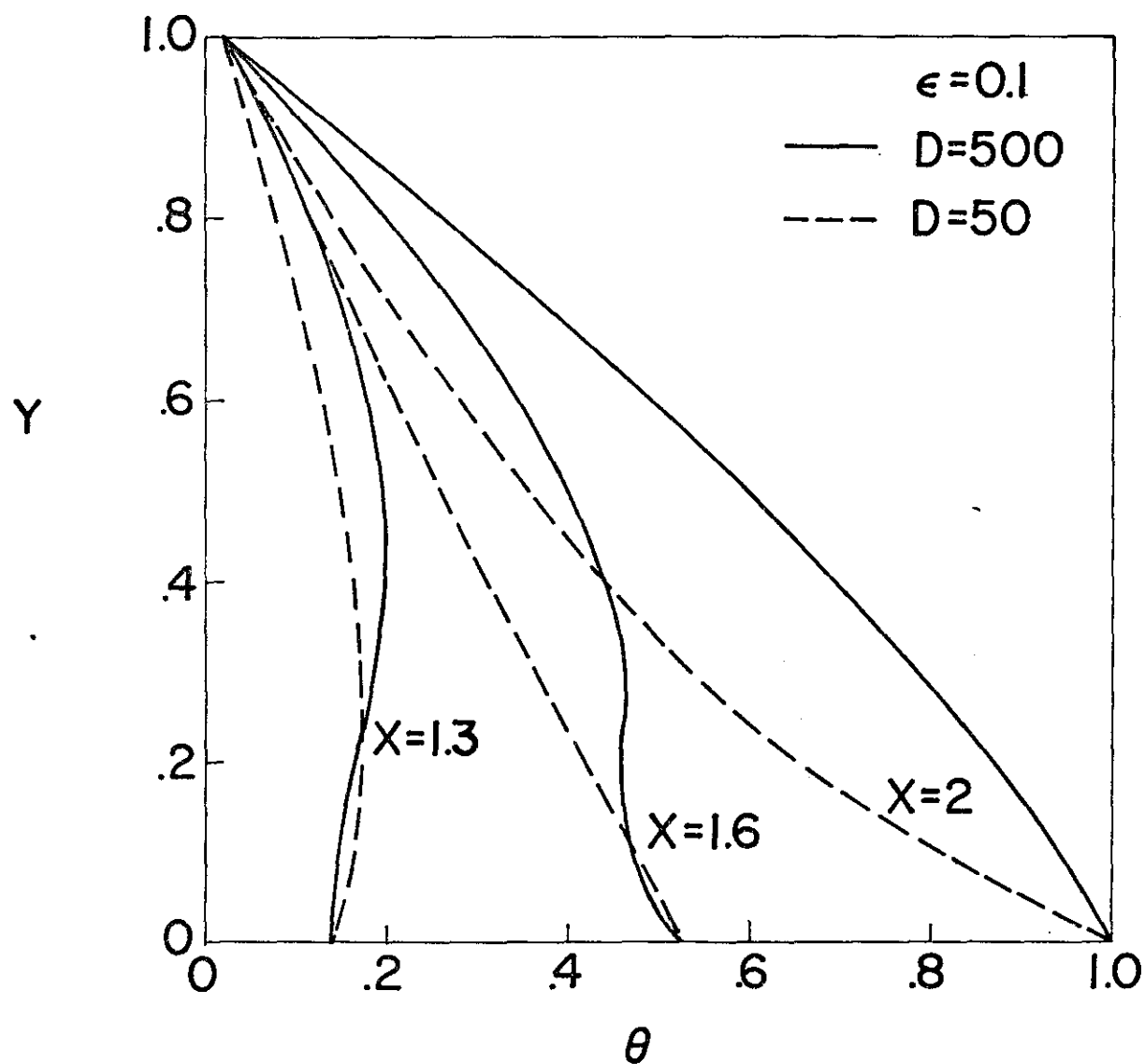


FIG. 3.1-5 EFFECT OF DISCHARGE NUMBER ON VERTICAL TEMPERATURE PROFILES FOR CASE 1

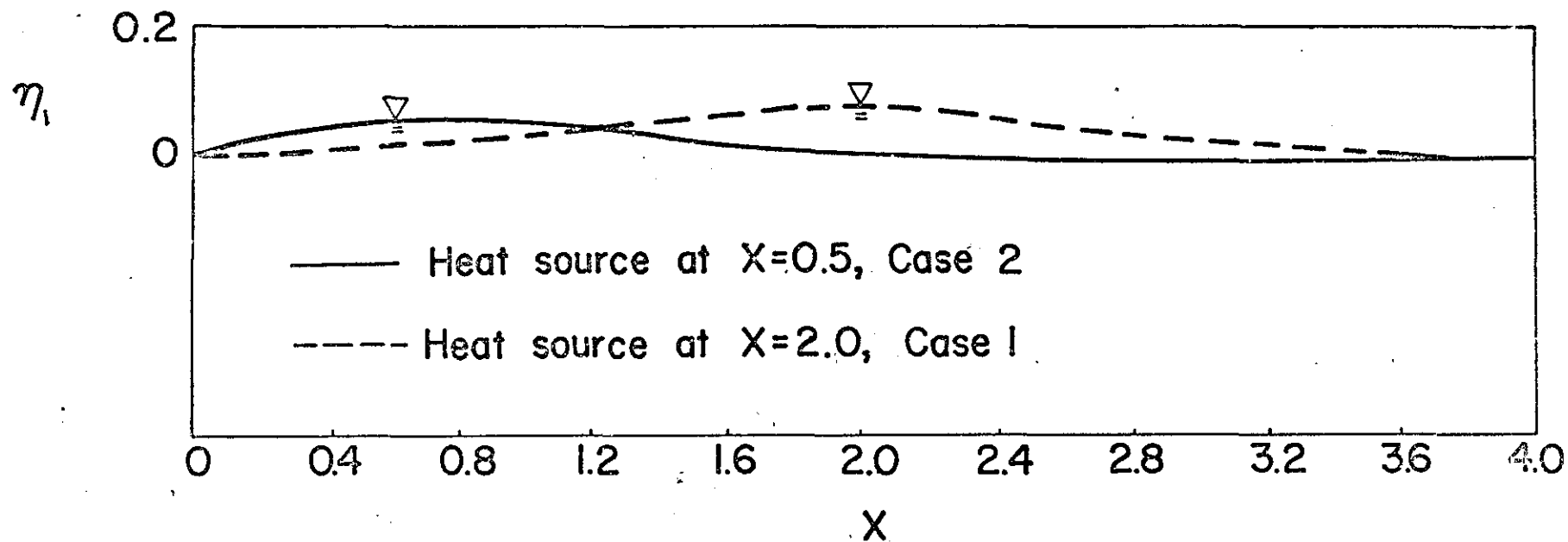


FIG. 3.1-6A EFFECT OF THE LOCATION OF HEAT SOURCE ON THE FIRST-ORDER PERTURBATION FUNCTION FOR THE UPWELLING OF WATER TABLE

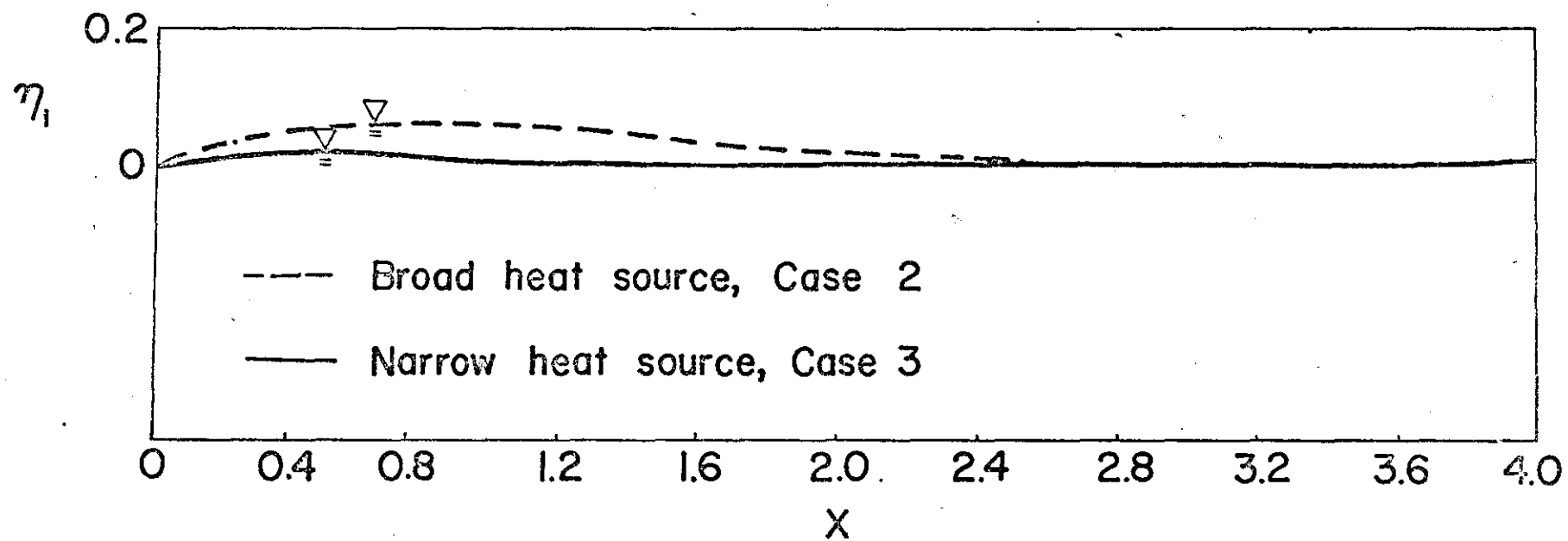


FIG. 3.1-6B EFFECT OF THE SIZE OF THE HEAT SOURCE ON THE FIRST-ORDER PERTURBATION FUNCTION FOR THE UPWELLING OF WATER TABLE

as  $D$  increases, the numerical results do give a qualitative, and yet conservative estimation. Thus, it can be concluded that (1) for a geothermal reservoir 1 mile deep with a heat source at  $800^{\circ}\text{F}$  and half mile in diameter, hot brine at  $400^{\circ}\text{F}$  can be found at half a mile below sea level if the drilling site is at the top of the heat source, (2) while the size of the heat source has an important effect on the temperature distribution in the reservoir, the location of the heat source has a small effect on the temperature distribution, (3) as a result of geothermal heating, cold seawater moves inland from the lower portion of the reservoir and warm water flows into the ocean from the upper portion of the reservoir, (4) heat transfer by convection is important in geothermal reservoirs. Thus the prediction of temperature distribution based on heat conduction will be in serious error, (5) the convection of heat is more efficient vertically than horizontally. This implies that the drilling site must be within the maximum temperature zone of the hot rock, (6) pressure in unconfined geothermal reservoirs can be estimated based on hydrostatic pressure, and (7) the upwelling of the water table is in the order of 100 feet for a reservoir of 1 mile in depth. The upwelling of water table as a result of geothermal heating is predicted analytically for the first time.

The perturbation method is used in the present analysis. The major advantages of the application of the method to the present problem are (1) the problem becomes linear and the difficulty in the non-convergence of iteration associated with the numerical solution of non-linear finite difference equations does not exist,

(2) the unknown position of the water table is explicitly determined from the first-order problem, thus the usual practice of the iteration of position of water table is avoided, and (3) a clearer physical picture emerged with regard to the driving forces and the role played by various parameters in heat transfer and fluid flow characteristics in a geothermal reservoir.

## 2. The Effects of Vertical Heat Sources on the Upwelling of Water Table

The perturbation approach discussed earlier was extended to investigate the effect of vertical heat sources on the upwelling of water table. The purpose of the analysis is to assess in a qualitative manner whether the upwelling of water table of 2000 feet above sea level reported by Keller [private communication] is due to vertical heat sources.

Suppose a dike exists in the reservoir as shown in Fig. 3.1-7A with the idealized situation shown in Fig. 3.1-7B. The governing equations are given by Eqs. (1-2). In addition to boundary conditions given by Eqs. (4-7), the boundary conditions on the dike are

$$\theta(x_{S_1}, Y) = \theta_S, \quad Y \leq Y_S \quad (9a)$$

$$\theta(x_{S_2}, Y) = \theta_S, \quad Y \leq Y_S \quad (9b)$$

$$\frac{\partial P}{\partial X}(x_{S_1}, Y) = 0, \quad Y \leq Y_S \quad (9c)$$

$$\frac{\partial P}{\partial X}(x_{S_2}, Y) = 0, \quad Y \leq Y_S \quad (9d)$$

$$\frac{\partial P}{\partial X}(X, Y_S) = -1 + \epsilon \theta_S, \quad x_{S_1} \leq X \leq x_{S_2} \quad (9e)$$

$$\theta(X, Y_S) = \theta_S, \quad x_{S_1} \leq X \leq x_{S_2} \quad (9f)$$



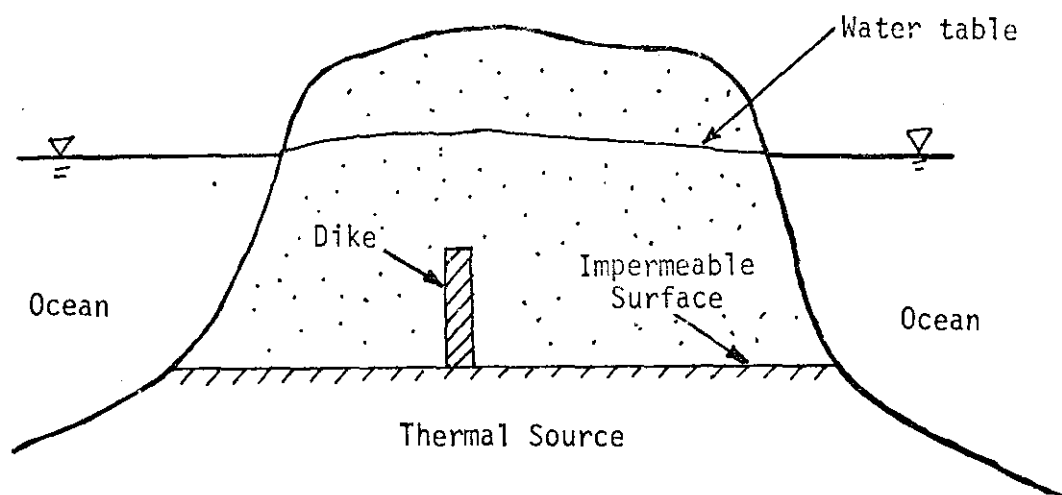


FIG. 3.1-7A UNCONFINED AQUIFER WITH A VERTICAL DIKE

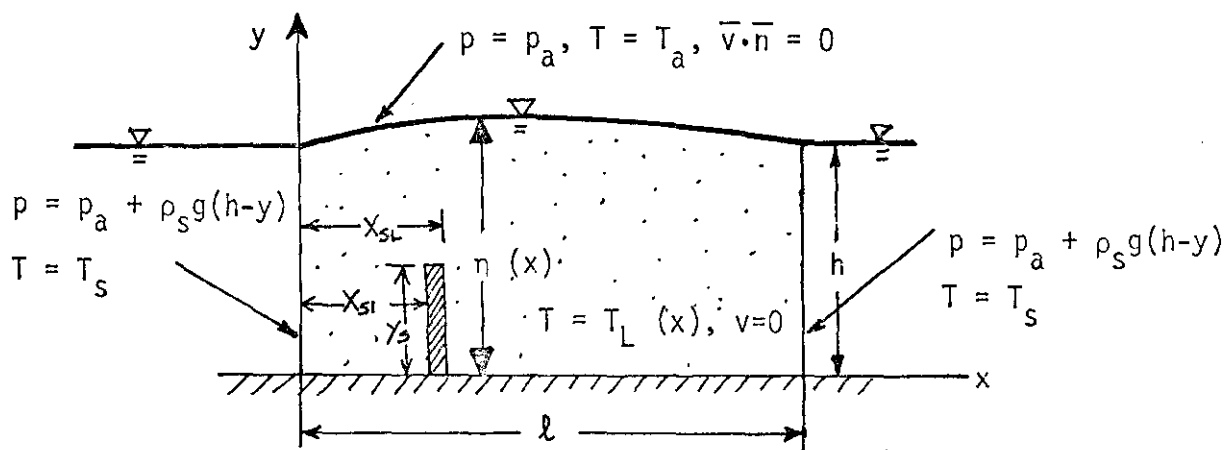


FIG. 3.1-7B IDEALIZED RECTANGULAR MODEL OF AQUIFER WITH A VERTICAL DIKE

where  $\theta_S$  is the prescribed dimensionless temperature of the dike. As a result of the perturbation technique described earlier, a set of linear equations is obtained. The resultant equations can then be solved numerically based on the finite difference method. Computations were carried out for the following two cases:

A. Vertical heating only

$$\theta_S = 1, \quad 0 \leq Y \leq 0.5,$$

B. Horizontal and vertical heating

$$\theta_L(X) = \exp\left[-\left(\frac{X-2}{0.5}\right)^2\right], \quad 0 < X < 1.9, \quad 2.2 < X < 4$$

$$\theta_S = 1, \quad 0 \leq Y \leq 0.5, \quad 1.9 \leq X \leq 2.1$$

Results of these computations along with previous results for horizontal heating are compared in Figs. 3.1-8, 3.1-9, 3.1-10. Fig. 3.1-8 shows the contours of stream functions for Cases A, B, and C where C referred to the previous results obtained in Technical Report No. 2. It is shown that the stream functions of the three cases exhibit similar behavior. The comparison of temperature contours for the three cases with  $D = 500$  and  $\epsilon = 0.1$  are plotted in Fig. 3.1-9 where it is shown that hot water at shallow depth is possible whenever there is a hot vertical heat source. The effects of vertical and horizontal heating on the upwelling of water table are shown in Fig. 3.1-10 where it is shown that the amount of upwelling increases for a vertical source. However, the upwelling of 2000 feet seems to be unlikely. A manuscript covering this work is now under preparation, and will be submitted for publication in a journal.

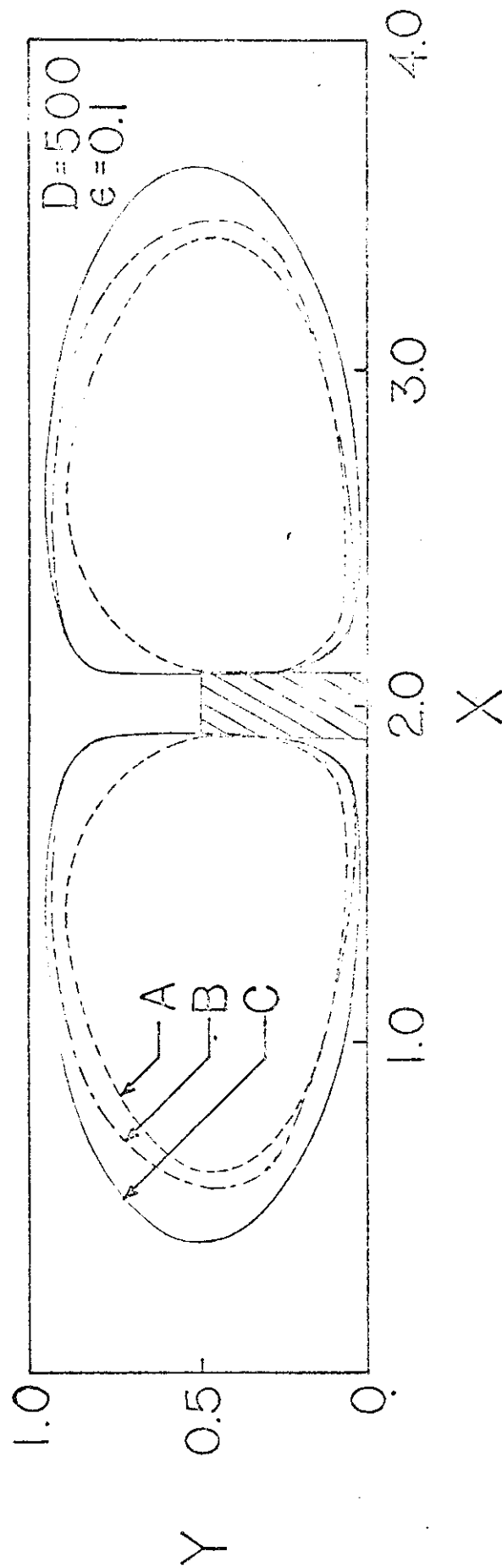


FIG. 3.1-8 EFFECTS OF VERTICAL AND HORIZONTAL HEATING ON STREAM LINES

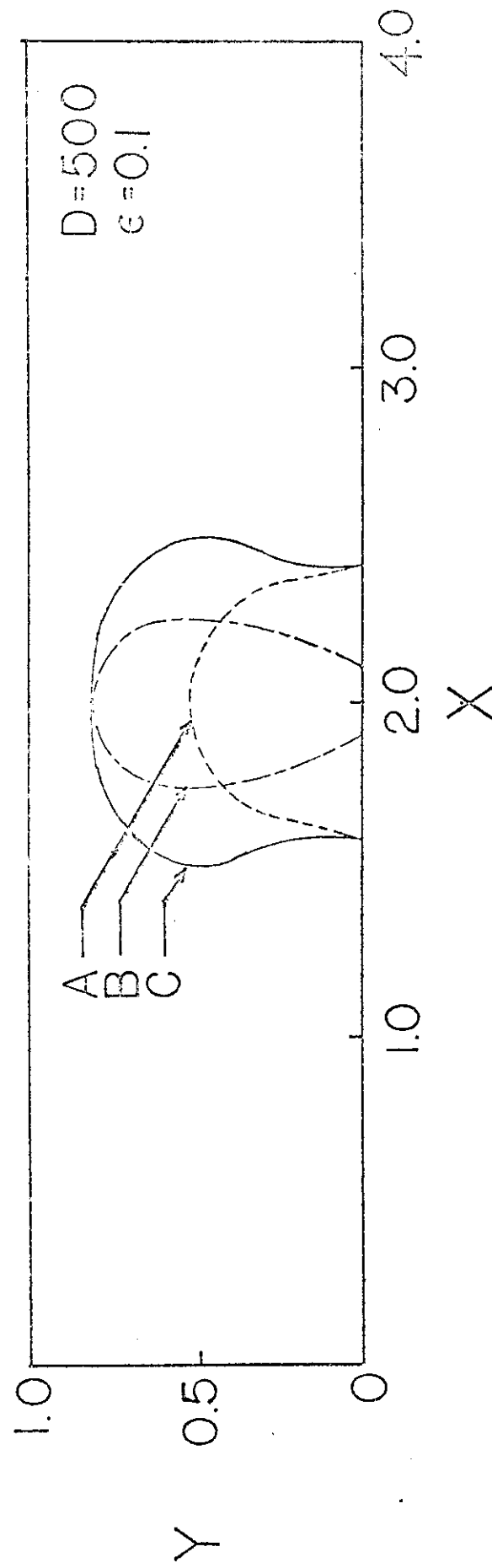


FIG. 3.1-9 EFFECTS OF VERTICAL AND HORIZONTAL HEATING ON TEMPERATURE CONTOURS

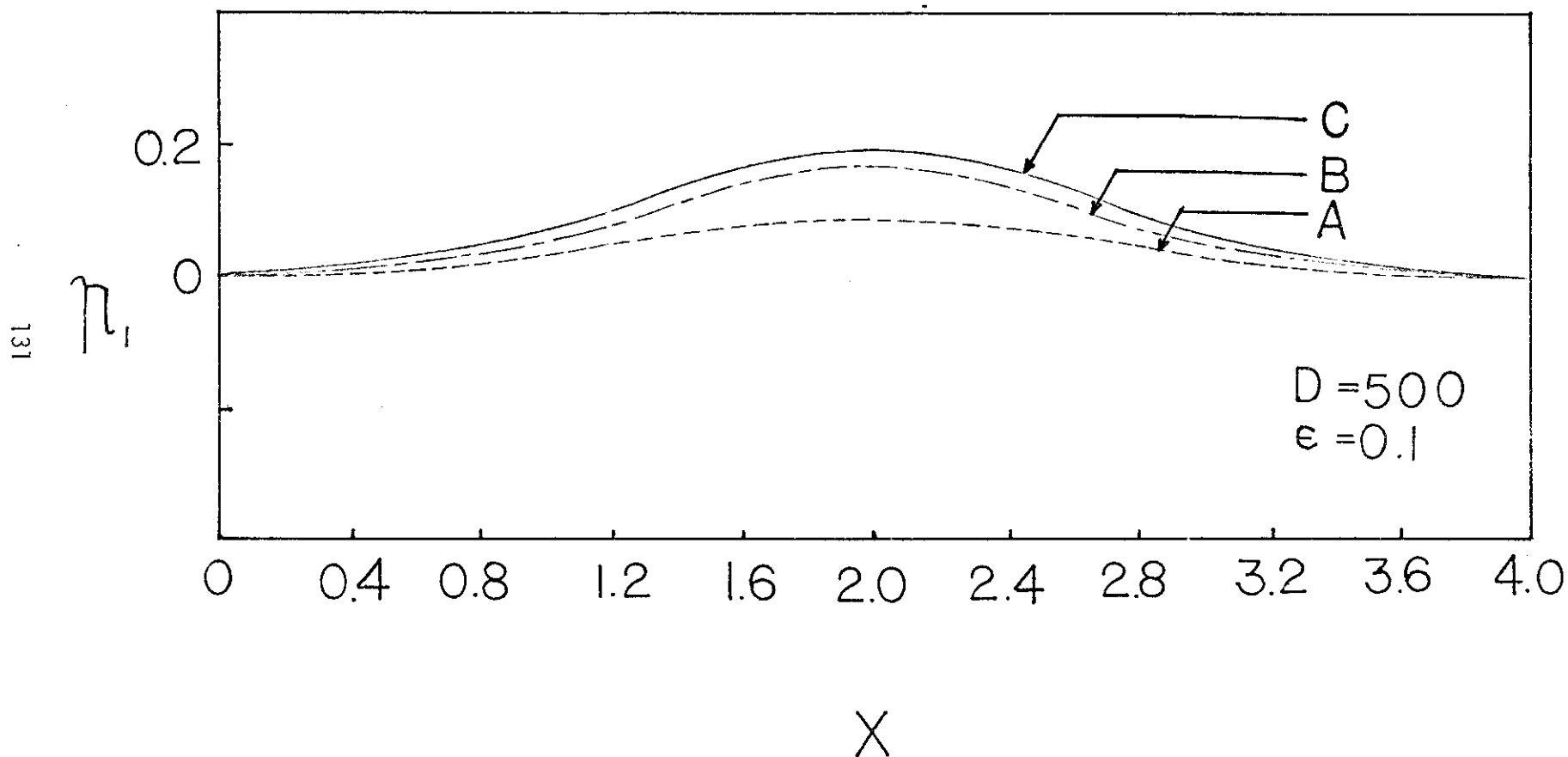


FIG. 3.1-10 EFFECTS OF VERTICAL AND HORIZONTAL HEATING ON THE FIRST-ORDER  
PERTURBATION FUNCTION FOR THE UPWELLING OF WATER TABLE

### 3. Heat Transfer and Fluid Flow Characteristics in an Axisymmetric Geothermal Reservoir

To have a qualitative understanding of the three-dimensional effects of seepage from the ocean on the temperature distribution in geothermal reservoirs, a study has been undertaken for the idealized case of an axisymmetric configuration. The formulation of the problem is similar to Eqs. (1-8) except that they are written in cylindrical coordinates. Numerical computations for  $L = 4$ ,  $D = 500$ , and  $\varepsilon = 0.1$  were carried out. The comparison of temperature contours and vertical temperature profiles between an axisymmetric reservoir and a rectangular one is shown in Fig. 3.1-11 and 3.1-12 where solid lines are for axisymmetric reservoirs and dotted lines are for rectangular ones. It is shown in these figures that temperature in a rectangular reservoir is considerably higher than that in an axisymmetric reservoir due to the three-dimensional seepage effect. Consequently, the upwelling of water table due to geothermal heating is smaller for axisymmetric reservoirs than that of rectangular reservoirs as is shown in Fig. 3.1-13.

In addition to the three problem areas discussed above, work has been initiated on the problems of pumping and reinjection in rectangular reservoirs, and on the finite element formulation of free convection in geothermal reservoirs with irregular boundaries.

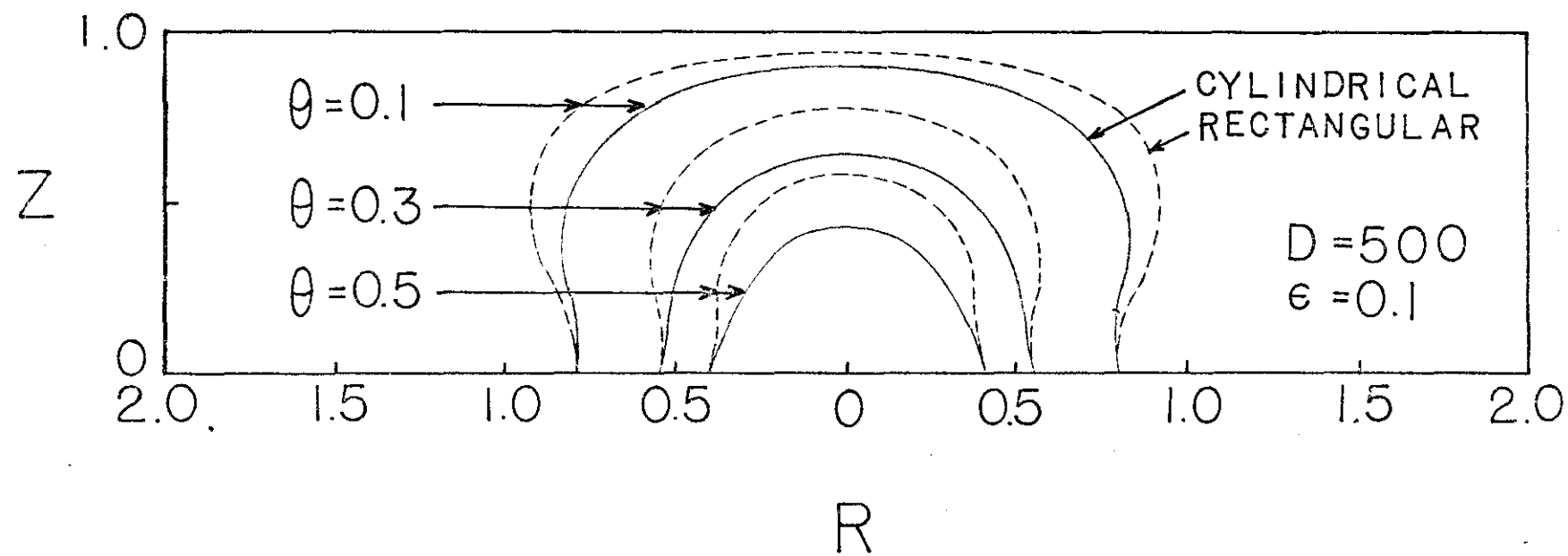


FIG. 3.1-11 EFFECT OF CONFIGURATION OF RESERVOIR ON TEMPERATURE CONTOURS

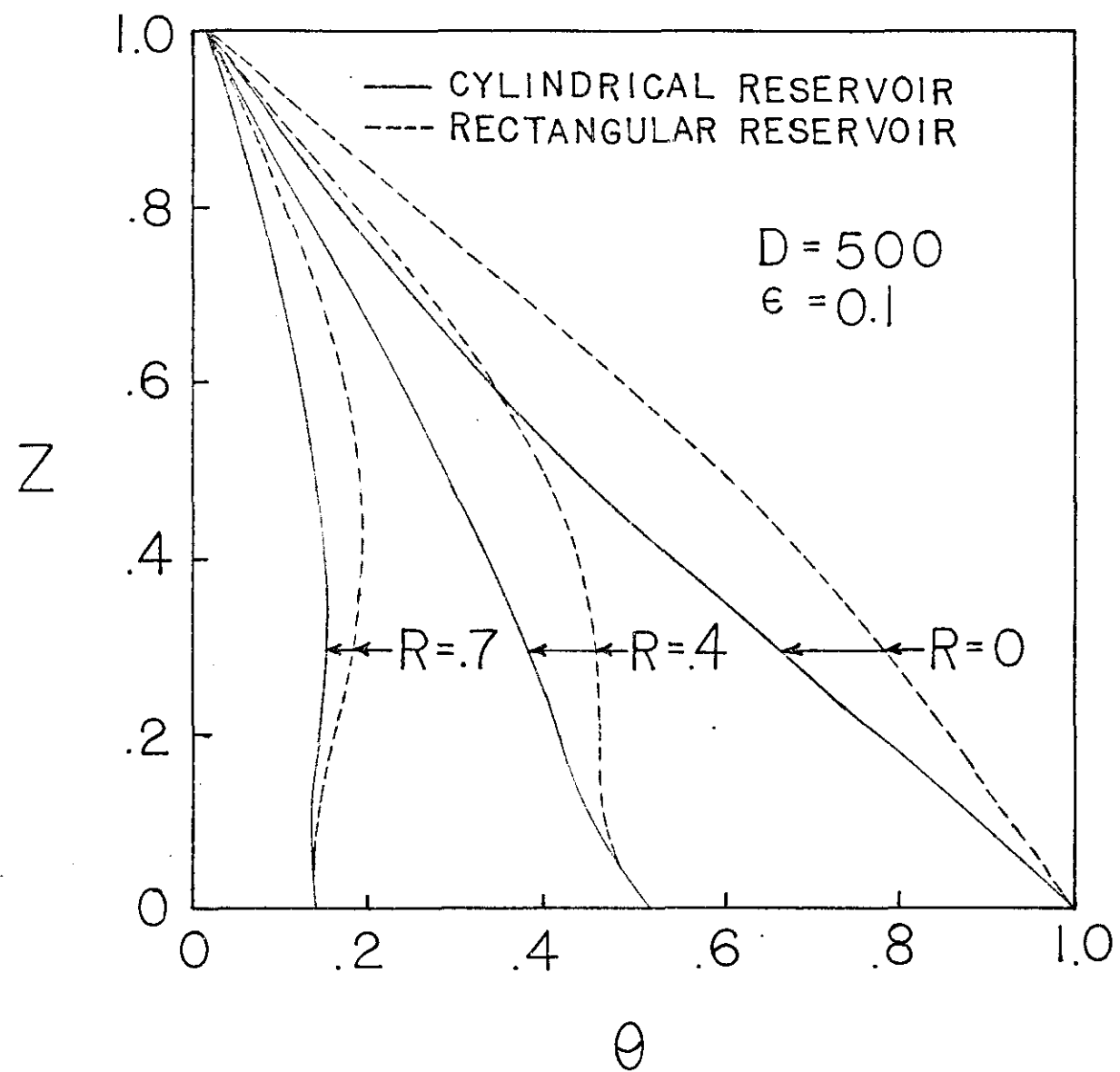


FIG. 3.1-12 EFFECT OF CONFIGURATION OF RESERVOIR ON VERTICAL TEMPERATURE PROFILES



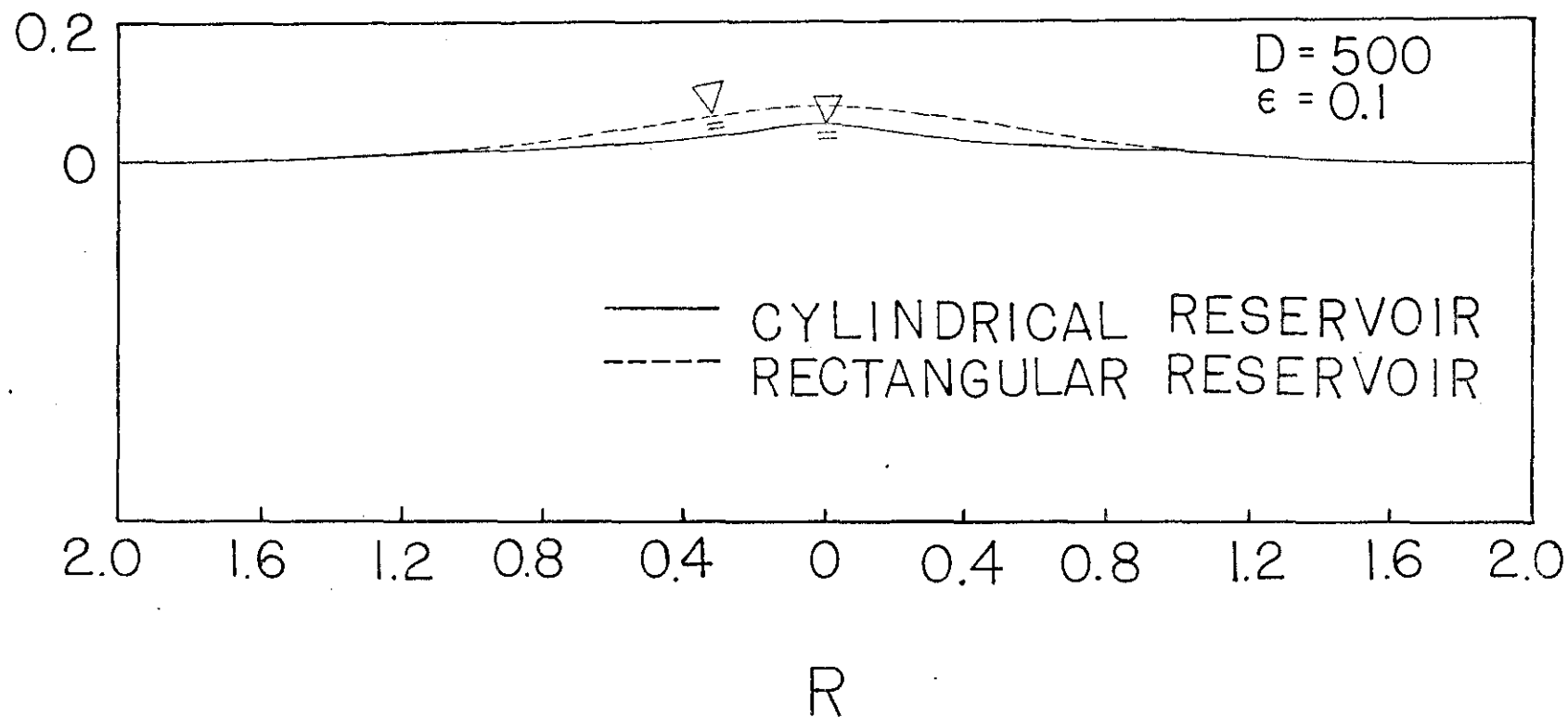


FIG. 3.1-13 EFFECT OF CONFIGURATION OF RESERVOIR ON THE FIRST-ORDER PERTURBATION FUNCTION FOR THE UPWELLING OF WATER TABLE

## 2. Well Test/Analysis & Physical Modelling

Investigators: B. Chen, L. S. Lau, & P. Takahashi

The research sub-tasks on well test/analysis and physical modelling have defined three areas of focus: hardware evaluation, software evaluation and development, and physical modelling. The following accomplishments can be reported:

1. characterization of the nature of geothermal reservoirs and completion of a survey on geothermal reservoir engineering, including an international questionnaire on the state-of-the-art in geothermal engineering,
2. survey on the availability and relative cost of hardware for geothermal fluid and environment measurement,
3. training program initiated to acquaint task members with the principles of well testing, analysis and performance prediction, with special emphasis placed on hands-on experience,
4. preliminary design of a physical model,
5. coordination with geophysical drilling program established to insure that all necessary analytical parameters are measured.

The following work is in progress:

1. continuance of training program,
2. frequent interchange with geophysics,
3. survey on availability of software for well analysis and performance prediction,
4. detailed analysis into the techniques of well testing,
5. development of a physical model.

A discussion of the work in Phase I is given in Technical Report No. 3, Geothermal Reservoir Engineering: State-of-the-Art. The following is a brief summary of this report; additional details can be found in the report itself.

## 1. The Nature of a Geothermal Reservoir

The "state-of-the-art" in geothermal reservoir engineering is in the most part formative. Three groups in particular, though, have contributed well: New Zealand [1 - 27]\*, the U. S. Geological Survey [29 - 40], and Stanford University [41 - 47]. Also available are some individual investigations, as for example, Test Well Mesa [28] and Whiting's reservoir engineering study of Wairakei [48].

The primary reason why the literature is relatively sparse is that private companies treat geothermal well testing, the data, and methods of analysis as proprietary. Certain legal restrictions furthermore tend to preserve this form of classification.

Speculations on the nature of geothermal reservoirs can be found in the literature. Geothermal reservoirs can be characterized in several ways:

- A. Depletable (self-sealed) or regenerative (recharged),
- B. Physical state,
  - 1) vapor - steam,
  - 2) liquid - hot-water, normally two-phased at wellhead,
  - 3) solid - hot rock,
  - 4) liquid magma.
- C. Physical condition,
  - 1) temperature/pressure,
  - 2) size/depth,
  - 3) production.
- D. Degree of dissolved solid content.

In California, vapor dominated wells are considered to be depletable. A tax allowance is allowed under this classification. A decision has not yet been made on other types of wells. There is some reason to believe that all wells are at least partially regenerative because of the meteoric

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\* References are listed on pp. 154 to 157.

(rainwater) origin of geothermal fluids [49]. Furthermore, reports of measurable pressure drops in steam-dominated geothermal fields seen after rainfall lead one to suspect that perhaps fluid recharge could be significant.

Although vapor-dominated geothermal wells are generally contaminated with  $\text{CO}_2$  (primarily) and  $\text{H}_2\text{S}$ , there is little dissolved solid content. On the other hand, some of the hot water well samples in the Imperial Valley have shown as much as 30% dissolved solids by weight.

There seems to be no clear cut answer to a universal definition of a geothermal reservoir. A geothermal reservoir needs:

- A. A heat source, magma or geopressure,
- B. To be confined in an aquifer, although non-permeable hot rocks can be transformed into an aquifer through hydrofracturing/thermal cracking and the addition of water,
- C. Caprock--to hold the hot fluid in place.

Speculations of how a geothermal reservoir might look have been advanced by White and Muffler [49, 50], U.S.; Facca [51], Italy; Elder [52], New Zealand; and Hayashida [53], Japan.

Although it has been reported that hot water reservoirs are twenty times more prevalent than vapor-dominated ones [56], technical difficulties in the former have resulted in considerably more production from the latter. Table 3.1-1 shows that five vapor, eleven hot water, and two binary cycle plants are either operating or close to completion [57]. Hot rock concepts are undergoing investigation by researchers from Battelle (for Montana) and the Los Alamos Scientific Laboratory (for New Mexico) [58]. Finally, a fourth concept, direct utilization of magma, was originally advanced by George Kennedy and David Griggs in 1960 [59]. A recent conference on volcano energy (Hilo, Hawaii) supported the reasonability of this latter scheme. Some preliminary work, mostly in the proposal stage, is being

TABLE 3.1-1 GEOTHERMAL PLANTS

DRY STEAM PLANTS	MW CAPACITY	INITIAL OPERATIONS
Italy		
Lardarello	365	1904
Monte Amiata	25	1967
U.S.A.		
Geysers, California	411	1960
Japan		
Matsukawa	20	1966
Hachimantai	10	1975
FLASHED STEAM PLANTS	MW CAPACITY	INITIAL OPERATIONS
New Zealand		
Wairakei	192	1958
Kawerau	10	1969
Japan		
Otake	13	1967
Hatchobaru	50	late 1970's
Mexico		
Pathe	3.5	1958
Cerro Prieto	75	1973
Iceland		
Namafjall	3	1969
Hengrill	13-32	late 1970's
Philippines		
Tiwi	10	1969
USSR		
Pauzhetsk	6	1967
El Salvador		
Ahuachapan Field	30	1975
BINARY CYCLE PLANTS	MW CAPACITY	INITIAL OPERATIONS
USSR		
Paratunka	1	1967
U.S.A.		
Imperial Valley, California	10-50	1975-1980

advanced by researchers from Sandia (New Mexico), Lawrence Livermore Laboratory, and the University of Hawaii.

When calculating the usable energy in a geothermal reservoir, one should be aware that only 1% of the total energy is converted to electrical energy from a hot-water reservoir using present proven technology, and from 2% to 5% of a vapor-dominated reservoir can be converted to electricity [49]. It should nevertheless be realized that on an absolute energy scale, a liquid dominated reservoir, per cubic foot of reservoir, contains more energy than a vapor dominated one. Secondly, the thermal conductivity of rock precludes conduction as a mechanism for regenerating a geothermal well. For example, H. Ramey has reported that the net heat recharge rate in the Big Geysers is only 0.6% [60]. However, the possibility of extraordinary fluid convection through porous media as driven by circulating magma should not be discounted--thermal cracking of the cooled magma can result in high permeability.

The general nature of a geothermal reservoir seems to be fairly well understood. There is some contention on the self-sealed/regenerative issue. However, the "state-of-the-art" in a qualitative sense is sufficiently developed--quantitatively, though, the challenges are only now beginning to surface.

## 2. International Questionnaire on the State-of-the-art in Geothermal Reservoir Engineering

An international survey was initiated to determine the "state of the art" in geothermal reservoir engineering. Not only was valuable information obtained from the survey, but it is hoped that the effort will spark development of geothermal reservoir engineering in a spirit of intra/international cooperation.

Over twenty replies were received from companies, institutions, and government agencies in various countries which have geothermal energy production. While some of the responses were received through oral communication, the majority of them were in the form of personal correspondence. Many of the individuals chose to answer the questions by citing published technical literature. The significant responses are tabulated in matrix form in Table 3.1-2.

### 3. Preliminary Investigation into Geothermal Measurement Hardware and Technique

#### A) Measurement and Method of Analysis

The purpose of well testing and analysis is to collect enough information to reveal the nature of the reservoir and to determine the pertinent physical parameters which control the behavior of fluids in the reservoir. Some of the questions that need to be asked are:

- 1) What are the temperature and pressure ranges of the fluid in question?
- 2) What is the nature of the fluid; i.e., vapor, liquid or a mixture of both?
- 3) What is the chemical composition of the fluid?
- 4) What production rate can be maintained and what is the expected life of the reservoir?

After the drill site has been selected, a reservoir analysis and formation evaluation program should be outlined as follows:

- 1) Bore Hole Tests
  - (a) Geographical Logging
  - (b) Driller's Log
  - (c) Drilling Fluid and Cutting Analysis
  - (d) Coring and Core Analysis
  - (e) Drill-stem Tests
  - (f) Geochemistry Analysis

TABLE 3.1-2 RESPONSES TO INTERNATIONAL QUESTIONNAIRE

NAME AND AFFILIATION	WHAT IS THE NATURE OF A GEOTHERMAL RESERVOIR	WELL TESTING AND ANALYSIS	
		HARDWARE	SOFTWARE
B. C. McCabe Magma Power Company USA	In geothermal reservoir engineering, the theoretical information to determine the size or longevity of a geothermal field is a very inexact science. For steam and hot water reservoirs, no one knows what the % of replaceable heat is coming into the reservoir in proportion to the amount being withdrawn. Probably, the replacement heat is much greater than it is generally imagined.	No reply	No reply
142 W. K. Summers New Mexico Bureau of Mines USA	Geothermal fluids consist of two components: 1) meteoric water and 2) gases ( $H_2S$ and $CO_2$ ), rising from great depths. The mixture of the components occur in fractures. If the fractures are sufficiently close together, a well will produce routinely. Otherwise, only occasional wells will produce.	Petroleum or groundwater hydrology equipment can be used, as modified to incorporate temperature.	Computer technology is generally adequate, but software is dependent on adequate sampling of the flow continuum and the proper incorporation of the parameter temperature.
Giancarlo E. Facca Registered geologist Italy and USA	Geothermal fields are composed of: 1) a deep sequence of layers, heated by an underlying magmatic stock and which, in turn, heats the overlying porous strata, and 2) a very permeable layer with thickness, porosity and permeability of such an order as to allow the formation and the permanence of a system of convection currents in the water filling the pores of the rock, and 3) an impermeable layer over the reservoir.	Refer to United Nations and UNESCO publications in Appendix A (A10, A12, A17, A22, A23).	Refer to United Nations and UNESCO publications in Appendix A (A10, A12, A23, A26, A27, A28).



TABLE 3.1-2 (CONTINUED)

W. E. Allen Oil and Gas Conservation Commission (Arizona) USA	Refer to articles in Appendices A and B.	Refer to articles in Appendices A and B.	For the purpose of predicting well performance, there are no marketing companies in Arizona.
Robin Kingston Kingston, Reynolds, Thom, and Allardice, Ltd., New Zealand	Refer to United Nations publications in Appendix A.	Refer to articles by D.K. Wainwright (A11) and A.M. Hunt (A12) in Appendix A.	Prediction of well perfor- mance is a composition of permeability, temperature, reservoir capacity, and rate of flow. Permeability in geothermal terms depends on fracture zones much more than on porosity. Oil reservoir assessment tech- niques can in some applica- tions be modified for geothermal applications.
Enrico Barbier International Institute for Geothermal Research Italy	Refer to United Nations and UNESCO publications Appendix B (B16, B24).	Equipment and other hardware are generally not available.	The evaluation of the quality of a geothermal well is uncertain. Anal- ogies are generally made with existing wells.
J. L. Guiza Geothermal Resources Cerro Prieto Mexico	Geothermal fields are classified into two major groups: 1) sedimentary fields and 2) volcanic fields. In a sedimentary field the productive strata is a permeable sandstone interbedded by impermeable clay layers. The sandstone is saturated with meteoric water, and the heat flow is due to the faults and fissures of the granitic basement. In volcanic fields the possible product- ion mechanism is due to the water flow through fissures in the volcanic rocks being heated by a cooling magmatic body.	For the determination of reservoir parameters such as permeability index and porosity, the synergetic log named SARABAND is used. For temperature, pressure, and flow measurements the conventional systems (Kuster RPG and KTG instruments) are employed.	The performance in a well can be predicted by means of a hydrologic model modified by the temperature effect and taking into account the physical charac- teristics of the productive sandstone as well as the physical-chemical properties of the geothermal fluids. For the purpose of optimi- zing well locations, computer programs are used to simulate field production.

2) Well Completion Methods

3) Well Tests

- (a) Temperature Survey
- (b) Pressure Survey
- (c) Pressure Drawdown Test
- (d) Pressure Buildup Test
- (e) Flowrate and Enthalpy Measurements
- (f) Geochemistry Analysis
- (g) Well Interference Test

4) Reservoir Analysis and Formation Evaluation Interpretation

The petroleum industry has developed most of the above testing instruments and procedures. However, one cannot blindly use their methods to interpret the results of the tests to geothermal fields. A geothermal reservoir in general has a higher temperature than a petroleum reservoir. Furthermore, most of the petroleum reservoir analysis is based on isothermal conditions which do not hold in a geothermal field. Whiting [61] and Ramey [60] have successfully demonstrated that the regular volumetric balance method in petroleum engineering does not apply to geothermal reservoir but rather a material and energy balance method is needed.

In the general sense, software encompasses both computer programs and the standard type curve analysis. It appears that the methods of well analysis used in the petroleum and gas industries cannot be naively applied to geothermal systems.

The general analytical solutions for transient flow in petroleum reservoirs have been obtained for three different types of boundary conditions:

- (a) infinite reservoir, line source well,
- (b) bounded circular reservoir,
- (c) constant pressure outer boundary.

The actual solutions have been presented many times in the petroleum literature; e.g., Matthews & Russel, Pressure Buildup and Flow Tests in Wells.

The basic assumptions in obtaining these solutions can be summarized as follows:

- (a) Temperature is constant throughout the reservoir,
- (b) Fluids have small and constant compressibilities.

The solutions are generally presented by plotting pressure versus temperature on log-log type paper.

Horner [62], in his 1951 classic paper, developed a way to graph the pressure buildup test data versus time on semi-log paper. From this, one can calculate permeability, skin effect, flow efficiency, and static average pressure. However, a great deal of difficulty has been encountered when one tries to apply the theory to a specific problem. Horner's method requires one to estimate on the semi-log graph paper a straight line (i.e., the quasi-steady state condition). This can be extremely difficult since the onset of the straight line can be seconds, minutes, hours, days, or even weeks. One can never be sure that the straight line chosen is the right one.

Fortunately, this deficiency can be remedied by plotting the data against a log-log type curve. Ramey [63] has demonstrated that this method permits one to determine easily whether one's data are truly on the semi-log straight line.

The above analysis works very well for oil and gas wells subjected to the two assumptions stated before. One has to be careful when one

applies these methods to a geothermal reservoir situation or incorrect results will be obtained.

First, depending upon the reservoir condition and production rate, a geothermal reservoir may or may not be isothermal. If non-isothermal conditions prevail, then the above analysis needs modification in order to be useful.

Secondly, there is a good possibility that the fluid flow in the reservoir may be two-phased. One has to develop the appropriate curve to take this effect into account.

Finally, in general one cannot completely shut in a geothermal well; therefore, a multirate flow test technique has to be used.

Well test analysis, though, can perhaps best be summarized by quoting Alex Muraszew, writing on "Geothermal Resources and the Environment," in the 1972 GEOTHERMAL WORLD DIRECTORY [64],

"....with the present state-of-the-art, neither the capacity of the reservoir nor its longevity can be accurately predicted...."

Fortunately, as undeveloped as this field is, definite progress is being shown. The Stanford Group has made admirable progress. A parallel laboratory study extending the work of Miller [65] and Cady [66] is being pursued at Stanford. The U.S.G.S. is devoting effort towards computer model studies with M. Nathanson, of the Menlo Park unit, beginning to publish. The University of Hawaii group is adding to this body of knowledge. The geo/hydrology group at California-Berkeley, has produced excellent computer models in this area.

In summary, the types of ongoing software analytical work include:

- 1) Prediction of performance and resources available from temperature and pressure data.

2) Reservoir simulation.

3) Well log analysis.

B) Hardware

Well tests are performed in two phases. In the first phase, tests are performed during open hole drilling operations. They consist of fluid temperature measurement, fluid sampling, core analysis, and formation logging. After completion, the producing well must undergo a second phase of tests to determine the thermodynamic condition of the fluid and the adequacy of the reservoir producing zone. Measurements are taken both at the wellhead and downhole.

The two well-test phases are:

1) Open hole tests

While the drilling operation is in progress the drilling fluid is continuously monitored for signs of increasing temperature gradient. The drill cuttings are also observed for indications of possible zones of fluid production. If temperatures begin to rise sharply with a corresponding increase in rock porosity, the drilling is stopped to perform a formation log. Simply described, in formation logging, a probe is lowered into a well at the end of a multiconductor cable and the physical parameters are measured and recorded as functions of depth to obtain well logs.

The three common forms of formation logs are electrical, sonic, and radioactive.

2) Producing well tests

After completion, the producing well must undergo a second phase of tests. The downhole tests consist of measuring fluid

parameters such as temperature, pressure, and flow rate.

See Figure 3.1-14. Although there are many ways of performing the tests, the two common methods are wireline operations and combination tool logging.

In wireline operations a measuring probe is lowered into a well at the end of a stainless steel cable. The surface equipment consists of depth measuring devices, weight indicators, line-speed indicators, and a motorized take up reel. The probe is made of a steel tubing with the recording and measuring instruments located internally. The recorder is attached to the end of the interchangeable measuring instruments as shown in Figure 3.1-14. The deflection of the stylus makes a mark on a black recording chart. After the probe is extracted from the well, the marks on the chart are read with a chart reader. Conversions to the desired parameter are made with a calibration table for each type of fluid measuring device.

Like most other logging instruments, the combination tool is lowered into a well at the end of a multiconductor cable. The fluid parameters are measured and, in turn, recorded automatically on the surface recorder equipment. The combination tool is ideally suited for a production well since the production flow profile has a relatively high rate as compared to a well in its exploratory stage.

While numerous types of tests may be performed in a production well, both the buildup and pressure drawdown tests

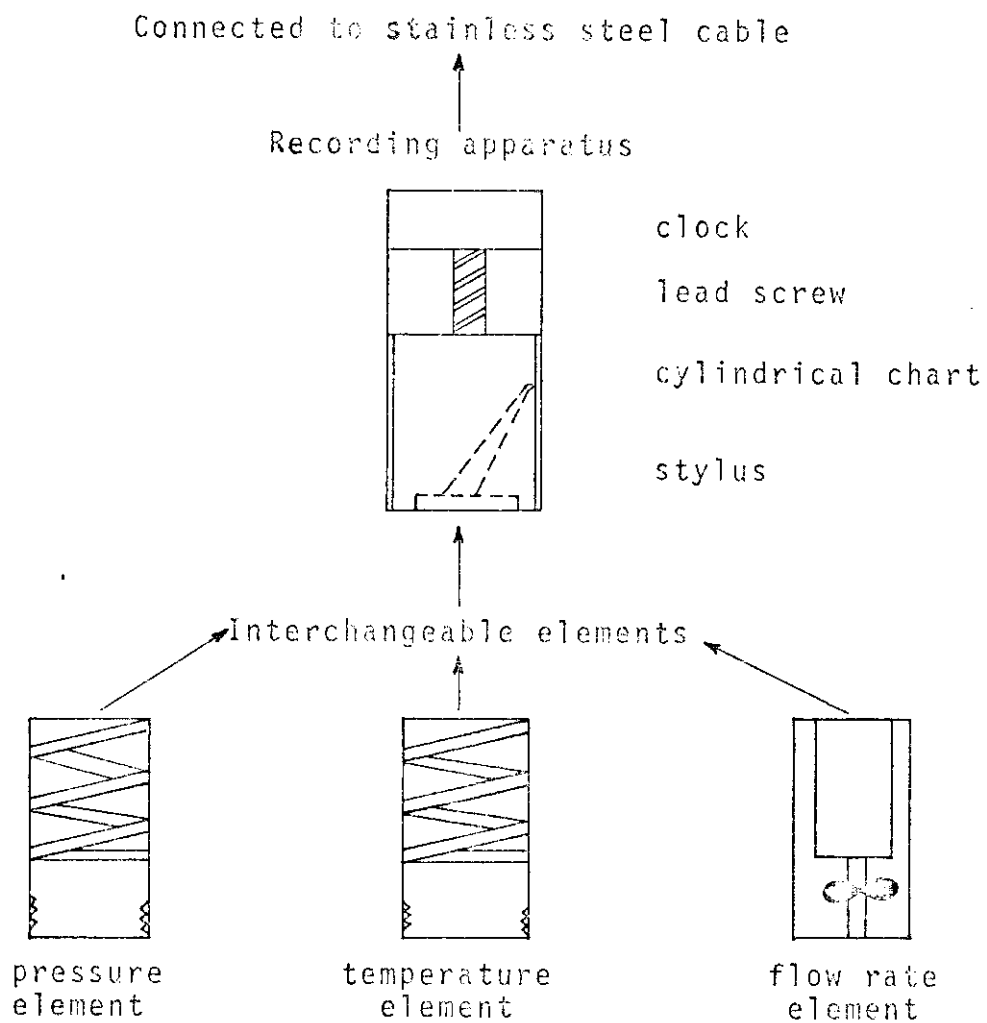


FIG. 3.1-14 SCHEMATIC DIAGRAM OF WIRELINE INSTRUMENTS

are of prime interest. The pressure behavior of a well is readily measurable and is a very useful property. Both types of tests are valuable tools for obtaining information about reservoir properties.

The theory of pressure buildup assumes a well is closed in, and that after it is closed in, no production enters the wellbore. Information such as the transmissivity (the product of the average permeability and the thickness of the reservoir), skin effects and flow efficiency can be estimated to aid the prediction of future production rate and production life of the reservoir. A pressure drawdown test consists of a series of pressure measurements made during a period of flow at a constant rate. An extended drawdown test should be run to estimate reservoir volume.

Correspondence has been initiated with various well test service companies and institutions. With the exceptions of Schlumberger and Kuster Company, most of the firms have had little experience in testing geothermal wells. The proprietary nature of the results has somewhat constrained information gathering. However, replies have indicated that Schlumberger and Kuster have the expertise to perform the task. Specifically, the logging methods are well developed by Schlumberger, and the Kuster Company has various types of wireline instruments for geothermal fluid measurement. With this fact in mind a preliminary commitment can be made to select the type of hardware for the two testing phases.



Since the initial testing phase consists of formation and packer tool logging, the services will probably be contracted out to a firm such as Schlumberger Well Service Company. The log interpreting computer program named SARABAND was developed by this firm, and it has been used successfully at Cerro Prieto and at Imperial Valley. The program interprets the log data and determines automatically the desired downhole parameters, and its use should be very helpful for the Hawaii Geothermal Project.

In the second testing phase the Kuster instruments will probably be used for the purpose of reservoir analysis. The cost of the instruments is about one tenth of the combination logging tool, and their reliability and sensitivity (0.4 psig for pressure and 0.3°F for temperature) are ideal for newly explored geothermal wells.

4) Preliminary analysis into the physical modelling of a geothermal reservoir

The physical model is a necessary balance to the ongoing software investigations. The physical model will not only serve as a convenient check on the computer model, but will simulate conditions not easily attempted by software. The objectives of the initial physical model studies will be to bring together known information about related laboratory studies, analyze the state-of-the-art, design the hardware system required for simulation, initiate fabrication, and conduct preliminary parametric tests.

Very little physical modelling work has been reported in the literature. The significant studies related to geothermal reservoirs include those of G. Cady [66], H. Henry and F. Kahout [67], and the remotely related work of J. Bear [68]. However, none of the reported investigations approached the problem on a total systems basis while considering the high temperatures expected.

In movement of fluid through a geothermal reservoir, the driving force is primarily the buoyant force. This force is created by heat within the geothermal system which decreases the fluid density.

The dimensionless number determined to be of prime interest to the study is the Rayleigh Number ( $N_{Ra}$ ). The Rayleigh Number is the product of the Grashof ( $N_{Gr}$ ) and Prandtl ( $N_{Pr}$ ) Numbers, where

$$N_{Gr} = \frac{\text{buoyant force}}{\text{viscous force}} \dots \dots \dots (1)$$

$$N_{Pr} = \frac{\text{momentum diffusivity}}{\text{thermal diffusivity}} \dots \dots \dots (2)$$

$$N_{Ra} = N_{Gr} \cdot N_{Pr} = \frac{\rho_s g \beta K (T - T_s) h}{\mu \alpha} \dots \dots \dots (3)$$

$$\text{where } \rho_s = \text{density of fluid}, \dots \dots \dots (4)$$

$$g = \text{gravitational constant}, \dots \dots \dots (5)$$

$$\beta = \text{coefficient of thermal expansion}, \dots \dots \dots (6)$$

$$K = \text{permeability of porous medium}, \dots \dots \dots (7)$$

$$(T - T_s) = \text{temperature driving force}, \dots \dots \dots (8)$$

$$h = \text{depth of permeable bed}, \dots \dots \dots (9)$$

$$\mu = \text{viscosity of fluid}, \dots \dots \dots (10)$$

$$\alpha = \text{thermal diffusivity of fluid} \dots \dots \dots (11)$$

The literature is sparse on the range of Rayleigh Numbers meaningful to actual geothermal systems. In general the study will investigate the range of  $N_{Ra}$  between 30 and 1000. This will be accomplished by altering the permeability of the solid medium and the temperature of the system. The permeability can be altered by changing the mesh size of the sand or glass bead bed. The temperature change will in turn determine the values of the coefficient of thermal expansion ( $\beta$ ), thermal diffusivity ( $\alpha$ ), viscosity ( $\mu$ ), and density ( $\rho$ ) of the fluid.

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### TASK 3.6 OPTIMAL GEOTHERMAL PLANT DESIGN

Investigators: H. C. Chai, J. Chou & D. Kihara

#### 1. Heat Balances

The design of a power plant is dictated by economic justification in a competitive society. Economic designs can be achieved only by careful analysis of all the possible solutions for a given situation. Such analysis is usually started from heat balances of various plant schemes to establish the respective heat rates and equipment sizes. Heat balances have been made to evaluate the effects of superheating geothermal steam by auxiliary fuel and using deep ocean water as cooling water in a condenser.

The presence of moisture in steam could reduce the turbine efficiency and cause the erosion of turbine blading. By superheating the low-pressure geothermal steam, it is possible to have dry exhaust steam. It was found that the heat rates of auxiliary fuel for superheating are comparable to the heat rates of modern central power plants.

For a geothermal plant near the sea, the cost of using sea water as cooling water in a condenser is likely to be lower than the cost of recycling the cooling water through a cooling tower. The average temperature of sea water is about 80°F at the surface and 40°F at a depth of 1,000 ft. Since the enthalpy drop per unit temperature at the low-pressure end of a steam turbine is much larger than that at the high-pressure end, the gain in power output by using deep-ocean water for cooling was found impressive.

#### 2. Optimal Operating Procedures of Vapor Flashing Plant

In a vapor flashing system, hot water is flashed to vapor in



cyclone separators at pressures lower than wellhead pressure. The vapors thus generated are used to drive a mixed-pressure turbine. The lower the flashing pressure, the higher the production rate of vapor. However, available energy associated with each pound of steam decreases with lowering of the separator pressure. A maximum power output exists for a certain combination of the operating pressures of separators. A numerical method has been worked out to optimize the operating pressures with consideration of different degrees of flashing efficiency and heat losses. In general, the temperatures which correspond to the vapor pressures in separators should be about equally distributed as suggested by Hansen [1]; for example, the optimum operating temperatures of a three-stage flashing plant are 380°F, 280°F and 100°F if the saturated temperature of input brine is 400°F and the exhaust from the turbine condenses at 120°F.

The number of flashing stages is a matter of economic justification. Power contribution of an additional stage decreases as the number of stages increases. The total work of a four-stage flashing is only 5% higher than that of a three-stage flashing for the saturated well water at 400°F and the turbine exhaust at 120°F.

### 3. Flow Rate of Hot Water Wells

The parameters which affect the production from a liquid-dominated aquifer are pressure and temperature of reservoir, depth of well, drawdown pressure, wellhead pressure, diameter of well and surface friction. The interrelationship among these parameters has been studied with a simplified procedure for the calculations, which will be improved shortly. The projected results should be helpful to the interpretation of well testing data and to the selection of the operating pressure of a self-flowing well.

Problems of pumping hot brine from a well have also been considered. It appears there is no commercial equipment available for forcing the hot brine out from a very deep well, although some pump manufacturers showed an unusual degree of interest in the development of submersible pumps to handle hot brines.

#### 4. Regenerative Binary Cycle

The word binary is used because two fluids are involved in the power production process, the geothermal fluid and the working fluid. There is an increasing interest in the utilization of heat from hot brine at 250°F to 450°F by using a fluid, such as Freon or isobutane, as the working fluid to operate in a closed Rankine cycle. To improve the basic cycle, such as that shown in Fig. 3.6-1, addition of a regenerative heat exchanger is proposed. Its function is to interchange the energy between the superheated exhaust from turbine and the condensate to be returned to the boiler. This study has shown that a regenerative isobutane cycle can significantly reduce the heat rejection from the plant and may lower the cost of power produced. Furthermore, the discharge temperature of brine in a regenerative cycle is much higher than that in a basic cycle; thus the waste heat can be used for producing fresh water with a multiple-effect evaporator as illustrated in the flow diagram of Fig. 3.6-2, which shows that nearly one-half of the hot brine can be converted into fresh water. For geothermal reservoirs located in areas where the supply of fresh water is inadequate, the combination of a regenerative isobutane power plant with a multiple-effect evaporator could be a sound solution to the compounded problems of power and water.

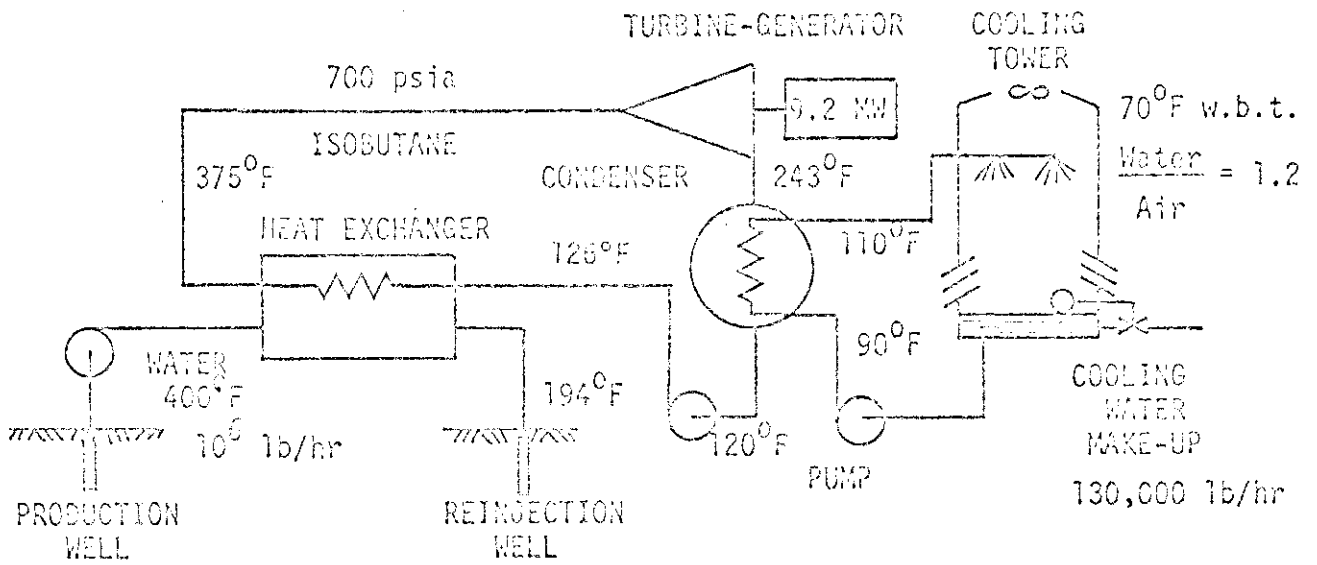
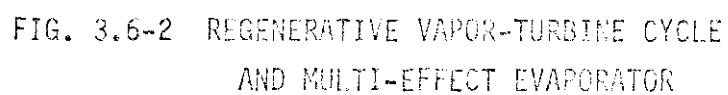


FIG. 3.6-1 BASIC ISOBUTANE CYCLE



In a liquid-dominated field, the geothermal fluid may be delivered from a well by flashing or by pumping. With a self-flowing well by flashing, the geothermal fluid appears in two phases at the wellhead, and the working fluid in a binary system should be heated in two stages. It is first heated by the geothermal liquid, then by the flashed vapor. As a case study, calculations have been made to determine the power outputs of a basic binary cycle and a regenerative binary cycle with two-phase water from the well under the following assumptions:

Rate of flow. . . . .	$10^6$ lb <sub>m</sub> /hr.
Temperature of water. . . . .	400°F.
Composition of water by weight. . . . .	20% vapor and 80% liquid.
Turbine efficiency. . . . .	85%.
Feed pump efficiency. . . . .	80%.
Minimum temperature difference in heat exchangers. . . . .	10°F.
Condensing temperature. . . . .	120°F.
Working fluid . . . . .	isobutane

At every throttle pressure, there is an optimum throttle temperature to yield the maximum power output. The results of calculations are tabulated in Tables 3.6-1 and 3.6-2. The highest power output in this case is at 700 psia throttle pressure. There is a significant increase in power output by using regenerative heat exchangers. The capital cost of a regenerator could be partly offset by the reduction of the size of the main heat exchanger. Since the heat rejection equipment is

TABLE 3.6-1 PERFORMANCES OF BASIC ISOBUTANE CYCLE

WORKING PRESSURE psia	OPTIMUM THROTTLE TEMP., °F	ISOBUTANE FLOW RATE 10 <sup>6</sup> lb <sub>m</sub> /hr	POWER OUTPUT MW	HEAT REJECTION 10 <sup>6</sup> BTU/hr	WATER LEAVING TEMP., °F
500	380	1.810	16.33	381.22	135
600	390	1.901	17.70	376.49	135
700	375	1.948	19.535	369.12	136
800	375	2.028	18.393	371.09	138
900	375	2.065	18.443	369.93	139

For 10<sup>6</sup> lb<sub>m</sub>/hr of two-phase water (20% vapor, 80% liquid) at 400°F,  
120°F condensing temperature.

TABLE 3.6-2 PERFORMANCES OF REGENERATIVE ISOBUTANE CYCLE

WORKING PRESSURE psia	OPTIMUM THROTTLE TEMP., °F	ISOBUTANE FLOW RATE $10^6 \text{ lb}_m/\text{hr}$	POWER OUTPUT MW	HEAT REJECTION $10^6 \text{ BTU/hr}$	WATER LEAVING TEMP., °F
500	380	1.996	18.013	264.87	245
600	390	2.076	19.33	275.52	230
700	375	2.101	21.07	283.01	217
800	375	2.183	19.819	294.02	210
900	380	2.223	19.862	303.94	200

For  $10^6 \text{ lb}_m/\text{hr}$  of two-phase water (20% vapor, 80% liquid) at  $400^\circ\text{F}$ ,  
 $120^\circ\text{F}$  condensing temperature.

a major cost item of geothermal power plants, the cost of regenerative cycle plants should be lower than the cost of basic cycle plants of the same capacity.

## 5. Heat Exchanger Design

Since one objective of a geothermal power plant is to maximize the power output for a given well production rate, initial efforts were concentrated on one of the factors limiting the conversion of thermal energy to electrical energy, i.e., the transfer of heat from the hot brine to the working fluid. However, many of the parameters that govern the performance of the heat exchange equipment are also parameters that affect the characteristics of the Rankine cycle, e.g., pressure, temperature, velocity of working fluid. Because of the interdependence of heat exchange characteristics and cycle performance, computer programs for these two areas were interfaced and run in tandem.

The computer programs modelling the system under consideration have the following characteristics:

### A. Rankine Cycle Computer Program

#### 1. Input

- a. Table of property values of working fluid
- b. Turbine inlet conditions; pressure and temperature
- c. Condenser inlet conditions; pressure and temperature
- d. Component efficiencies
- e. Required power output

#### 2. Output

- a. Property values of working fluid at all points in the cycle
- b. Cycle efficiency
- c. Mass flow rate of working fluid for required power output
- d. Heat rejection rate



## B. Boiler and Superheater Computer Program

1. Input
  - a. Properties of brine and working fluid
  - b. Brine inlet temperature and velocity
  - c. Working fluid inlet temperature and pressure
  - d. Pinch point temperature difference
  - e. Tube material, diameter, spacing
  - f. Fouling factors
2. Output
  - a. Convective heat transfer coefficients on both sides
  - b. Number and length of tubes required
  - c. Total heat transfer rate across tube walls
  - d. Ratio of mass flow rates - brine to working fluid

To observe general trends in the heat exchanger specifications, the preliminary design of a vertical counterflow heat exchanger was completed for a system having the following nominal conditions:

Heat source . . . . . Water at 350°F  
Working fluid . . . . . RbBr - 60% (RbBr)  
Pinch point temperature difference . . . 30°F  
Velocity of working fluid . . . . . 7 ft/sec.  
Condenser outlet . . . . . Saturated liquid at 100°F  
Turbine efficiency . . . . . 85%  
Pump efficiency . . . . . 75%  
Net power output . . . . . 10MW  
Pressure losses, heat losses, and fouling neglected

The hot brine is assumed to be circulating inside the tubes because of cleaning considerations. In the non-boiling section, the equation recommended by Kays [2] was used. In the boiling region, the correlation equation by Chen [3] was used.

In Figure 3.6-3, the minimum tube length required as a function of turbine inlet temperature is roughly 150 feet. The total number of tubes required is shown in Figure 3.6-4. For comparison purposes, the

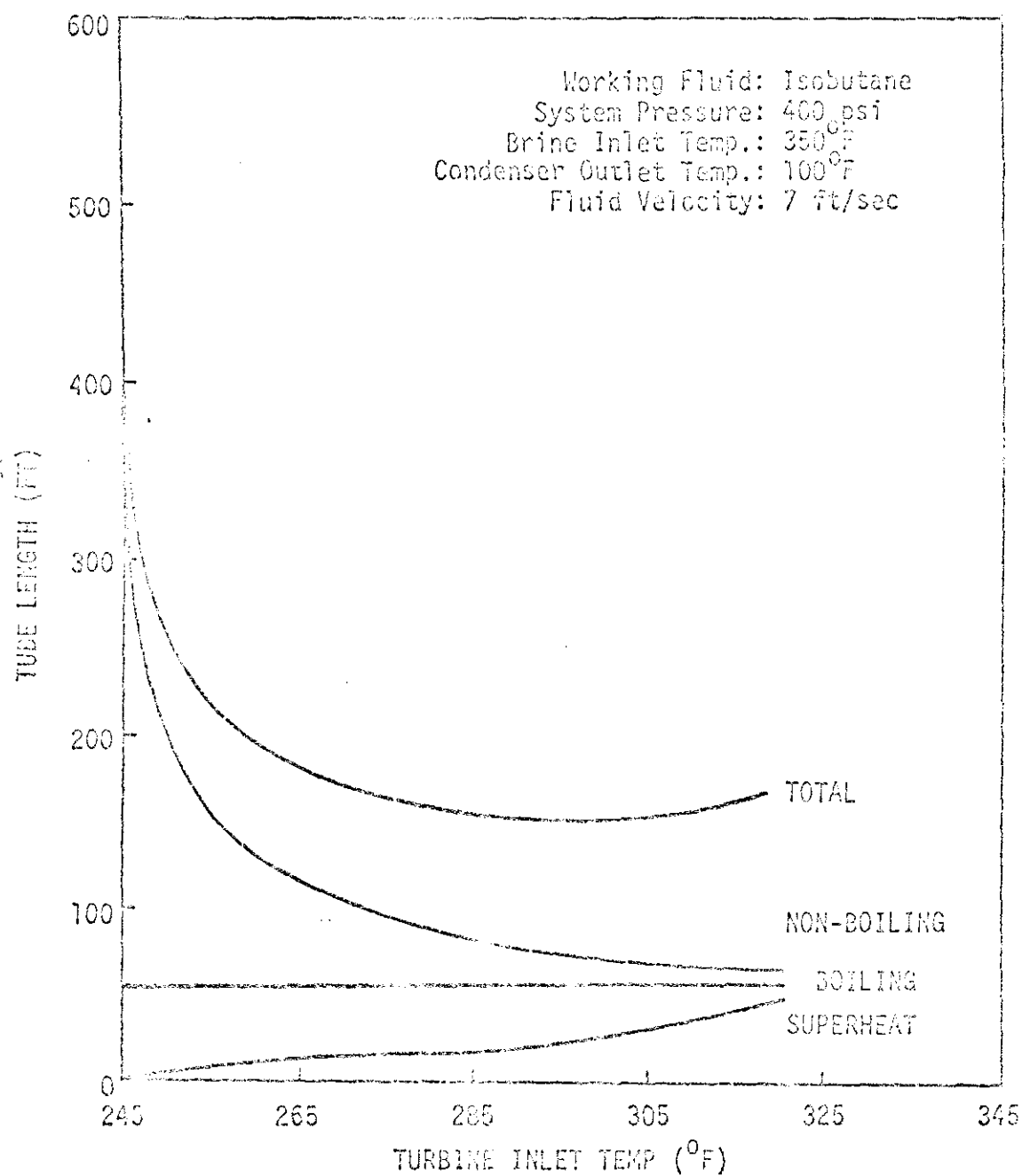


FIG. S.6-3 TUBE LENGTHS AS A FUNCTION OF  
TURBINE INLET TEMPERATURE

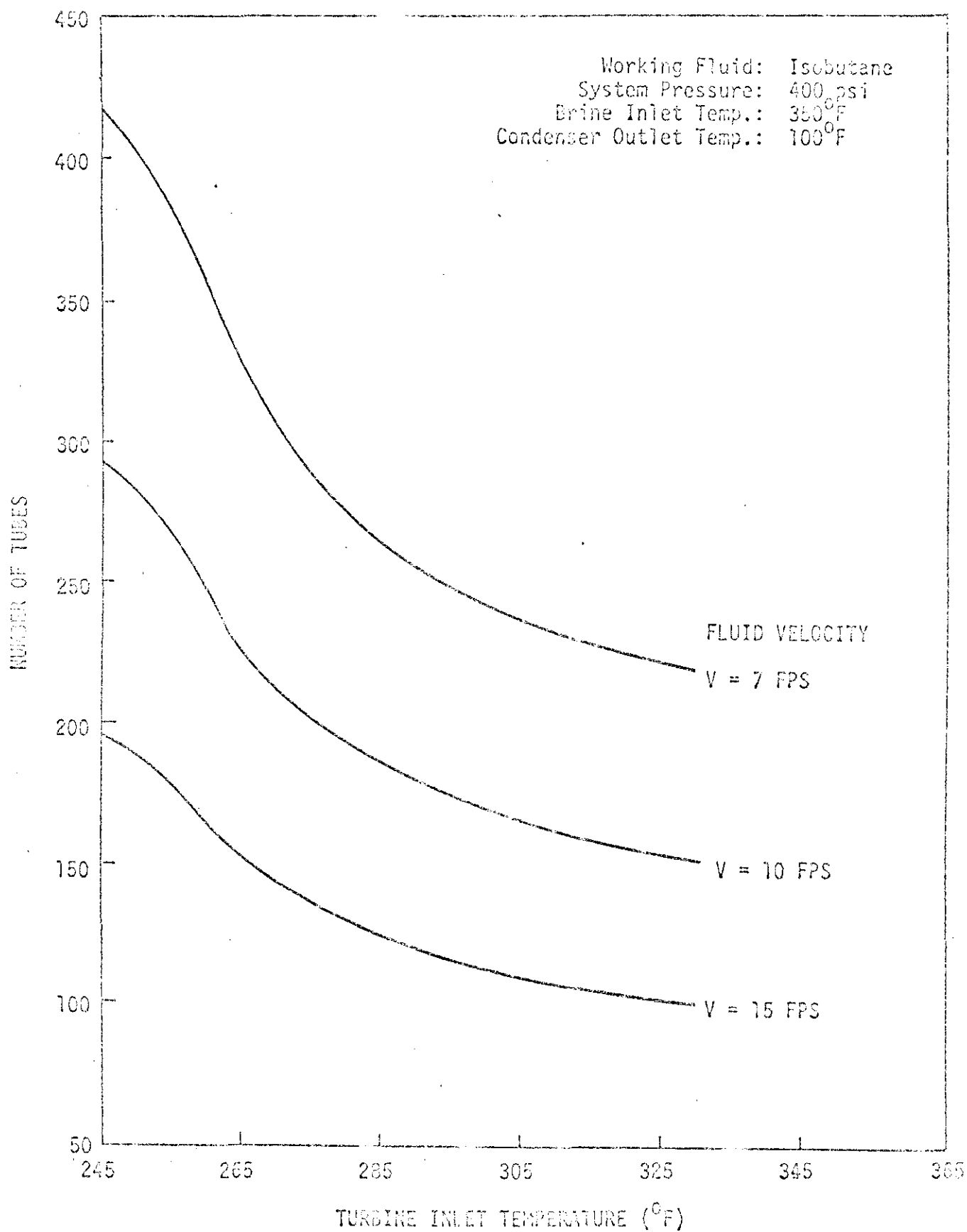


FIG. 3.0-4 NUMBER OF TUBES AS A FUNCTION OF TURBINE INLET TEMPERATURE

number of tubes required for other values of fluid velocity is also indicated. Figure 3.6-5 shows the pressure drop across the heat exchanger. It is interesting to note that a minimum value occurs at a turbine inlet temperature of approximately 500°F.

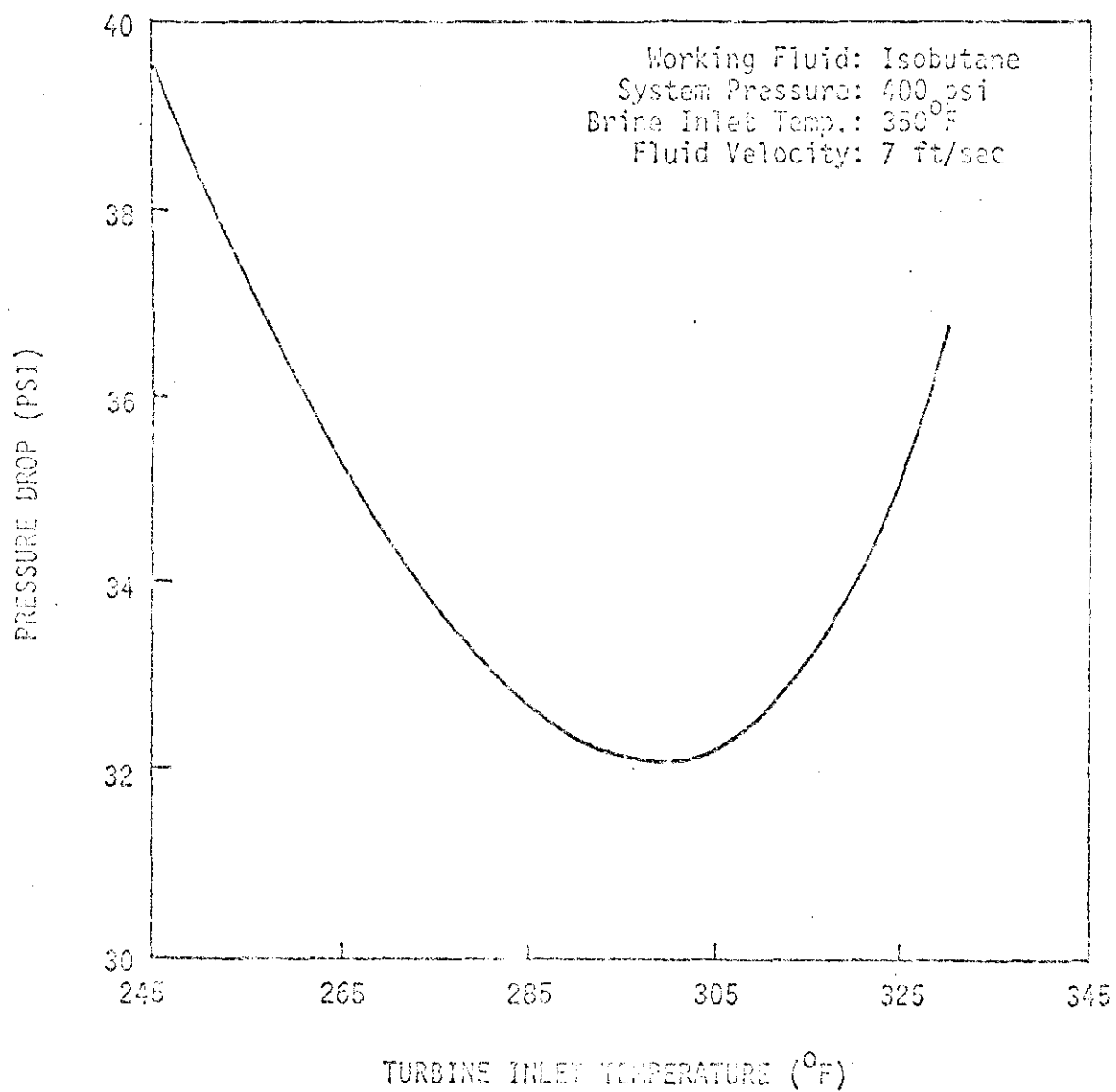


FIG. 3.6-5 HEAT EXCHANGER PRESSURE DROP  
FOR FLUID VELOCITY OF 7 FT/SEC

## PHASE II PROGRAM PLAN

The research proposed for the Engineering Program is primarily a continuation of work already in progress and summarized in the previous section. While these studies will be applied to the Hawaii geothermal reservoirs, the emphasis will continue to be on work of general applicability so that results can be utilized in other geothermal areas. Following are descriptions of the proposed research for each Engineering task, including task timetables.

## TASK 3.1 GEOTHERMAL RESERVOIR ENGINEERING

### 1. Numerical Modelling of Geothermal Reservoirs

Investigators: P. Cheng, K. H. Lou, & L. S. Lau

Experience gained during Phase I has built up the necessary background and capability to attack more difficult and more realistic problems in Phase II. Analytical studies of the geothermal reservoir for Phase II will be devoted to the following five problems:

#### a. Steady Pumping and Re-injection in a Hot-Brine Reservoir

Pumping and re-injection of fluids will undoubtedly influence the temperature distribution in a geothermal reservoir, especially in a region near the coast. The effects of pumping and re-injection rate and the location of pumping and re-injection sites on temperature distribution will be studied. During the initial phase of this work, we will focus our attention on pumping and re-injection in a confined geothermal reservoir. The corresponding problem for an unconfined reservoir with water table at the top will be studied subsequently. For a rectangular reservoir with a pumping well located at  $(x_1, y_1)$  at a pumping rate of  $Q_1$ , and a re-injection well at  $(x_2, y_2)$  with a re-injection rate of  $Q_2$ , it can be shown that the governing dimensionless equations are

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} - c \frac{\partial \theta}{\partial y} = \bar{Q}_1 \delta(x-x_1) \delta(y-y_1) - \bar{Q}_2 \delta(x-x_2) \delta(y-y_2) \quad , \quad (1)$$

$$\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + D \left\{ \frac{\partial p}{\partial x} \frac{\partial \theta}{\partial x} + \frac{\partial p}{\partial y} \frac{\partial \theta}{\partial y} + [1 - c(\theta - \theta_s)] \frac{\partial \theta}{\partial y} \right\} = 0 \quad , \quad (2)$$

Where

$$\begin{aligned} \delta's & \text{ are the delta functions, } \epsilon \equiv \beta T_c, \quad \theta \equiv \frac{T}{T_c}, \\ \bar{Q}_1 & \equiv \frac{Q_1}{\frac{\rho_s K g}{\mu}}, \quad \bar{Q}_2 \equiv \frac{Q_2}{\frac{\rho_s K g}{\mu}}, \quad P \equiv \frac{p - p_a}{\rho_s g h}, \quad D \equiv \frac{\rho_s K g h}{\alpha \mu}, \\ X & \equiv \frac{x}{h}, \quad Y \equiv \frac{y}{h}, \quad \theta_s \equiv \frac{T_s}{T_c}, \end{aligned} \quad (3)$$

with the subscripts "s", "a", and "c" denoting the conditions in the ocean, in the atmosphere, and at the maximum temperature of the impermeable surface. The quantities  $\rho$ ,  $\mu$ ,  $\beta$  in Eqs. (1-2) are the density, viscosity, thermal expansion coefficient of the fluid whereas  $\alpha$  and  $K$  are the thermal diffusivity and the permeability of the medium.

Boundary conditions along the ocean are

$$P(0, Y) = P(L, Y) = 1 - Y, \quad (4a)$$

$$\theta(0, Y) = \theta(L, Y) = \theta_s. \quad (4b)$$

Along the impermeable surfaces at  $Y = 0$ , &  $Y = 1$ , the boundary conditions are

$$\frac{\partial P}{\partial Y}(X, 0) = \frac{\partial P}{\partial Y}(X, 1) = -1 + \epsilon(\theta_L - \theta_s), \quad (5a)$$

$$\theta(X, 0) = \theta_L(X), \quad (5b)$$

$$\theta(X, 1) = \theta_a. \quad (5c)$$

If a power series in terms of  $\epsilon$  for  $P$  &  $\theta$  are substituted into Eqs. (1-5), and terms of like power in  $\epsilon$  are collected, we have a set of linear sub-problems that can be solved numerically based on the finite difference method.

#### b. The Dynamics of Ghyben-Herzberg Lens

In the Hawaiian Islands, the rain percolating through the ground will form a Ghyben-Herzberg lens of fresh water which rests on top of a sea water zone. The analysis of the dynamics of the Ghyben-Herzberg lens as a result of geothermal heating will be of fundamental interest.



If the fresh water and sea water are assumed to be miscible, it can be shown that the governing equations in terms of dimensionless pressure, temperature, and concentration are given by

$$\frac{\partial^2 P}{\partial X^2} + \frac{\partial^2 P}{\partial Y^2} = \epsilon_T \frac{\partial \theta}{\partial Y} - \epsilon_C \frac{\partial C}{\partial Y} , \quad (6)$$

$$\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} + D_T \left[ \frac{\partial P}{\partial X} \frac{\partial \theta}{\partial X} + \frac{\partial P}{\partial Y} \frac{\partial \theta}{\partial Y} \right] + D_T \left[ 1 - \epsilon_T (\theta - \theta_S) + \epsilon_C (C - 1) \right] \frac{\partial \theta}{\partial Y} = 0 , \quad (7)$$

$$\frac{\partial^2 C}{\partial X^2} + \frac{\partial^2 C}{\partial Y^2} + D_C \left[ \frac{\partial P}{\partial X} \frac{\partial C}{\partial X} + \frac{\partial P}{\partial Y} \frac{\partial C}{\partial Y} \right] + D_C \left[ 1 - \epsilon_T (\theta - \theta_S) + \epsilon_C (C - 1) \right] \frac{\partial C}{\partial Y} = 0 , \quad (8)$$

where  $P$ ,  $X$ , and  $Y$  are defined in Eq. (3) and

$$\begin{aligned} C &\equiv \frac{c}{c_S} , & \epsilon_T &\equiv \beta_T \Gamma_C , & \epsilon_C &\equiv \beta_C \Gamma_C , & D_T &\equiv \frac{\rho_S K g h}{\alpha \mu} , \\ D_C &\equiv \frac{\rho_S K g h}{\alpha_C \mu} . \end{aligned} \quad (9)$$

Boundary conditions along the ocean are given by

$$P(0, Y) = P(L, Y) = 1 - Y , \quad (10a)$$

$$\theta(0, Y) = \theta(L, Y) = \theta_S , \quad (10b)$$

$$C(0, Y) = C(L, Y) = 1 \quad (10c)$$

Along the impermeable surface, the boundary conditions are

$$\frac{\partial P}{\partial Y}(X, 0) = -1 + \epsilon_T (\theta_L - \theta_S) - \epsilon_C (C - 1) , \quad (11a)$$

$$\theta(X, 0) = \theta_L(X) , \quad (11b)$$

$$\frac{\partial C}{\partial Y}(X, 0) = 0 . \quad (11c)$$

Along the free surface  $Y=\eta$ , the boundary conditions are

$$\frac{\partial P}{\partial X} \frac{\partial \bar{\eta}}{\partial X} - \left[ \frac{\partial P}{\partial Y} + 1 - \epsilon_T (\theta_a - \theta_s) - \epsilon_c \right] - \epsilon_n = 0, \quad (12a)$$

$$P(X, \bar{\eta}) = 0, \quad (12b)$$

$$\theta(X, \bar{\eta}) = \theta_a, \quad (12c)$$

$$C(X, \bar{\eta}) = 0, \quad (12d)$$

where  $\epsilon_n = \frac{\mu N}{K \rho_s g}$  with  $N$  denoting the amount of accretion at the water table. Since  $\epsilon_T$ ,  $\epsilon_c$ , and  $\epsilon_n$  are small, the problems can be simplified on the basis of the perturbation method with  $\epsilon_T$ ,  $\epsilon_c$ , and  $\epsilon_n$  as the perturbation parameters. The resultant zero-order and first-order problems will also be linear and can be solved numerically using the finite difference method.

c. Transient Responses in a Hot-Brine Reservoir with Pumping and Re-injection

During the latter part of Phase II, work will be initiated on the study of transient responses in rectangular and axisymmetric geothermal reservoirs as a result of pumping and re-injection. This study will yield useful information on the effects of various parameters on the life span of geothermal reservoirs. As far as we are aware, no articles have been published to date on the study of unsteady temperature and pressure distributions in geothermal reservoirs as a result of pumping and re-injection.

d. The Effects of Anisotropic Properties of Rock Formation and Irregular Geometry

One of the major efforts during Phase II of the grant will be the writing of a general computer code for the simulation of Hawaii geothermal reservoirs, taking into consideration the anisotropic

properties of rock formation, the irregular geometry of the boundaries, and the presence of dikes. Inputs from geologists and geophysicists in the Hawaii Geothermal Project will be used to construct a more realistic model. The finite element method with Galerkin procedures will be employed to approximate the set of non-linear partial differential equations by a set of non-linear algebraic equations that can be solved numerically by iteration. To guarantee the convergence of the iteration process, numerical results from earlier work based on idealized models will be used as the input data for the first iteration. The computer program will be refined in steps to take into consideration pumping and re-injection, freshwater recharging, unsteady and three-dimensional effects. Detailed calculations will be made for the specific site under consideration in the Puna area.

e. Boiling Heat Transfer and Two-Phase Flow in Geothermal Reservoirs

In anticipation that some degree of boiling heat transfer will be present in Hawaii geothermal reservoirs, especially near the production well where pressure is low, a study on boiling heat transfer in a porous medium will be initiated during Phase II. The experience gained during Phase I dealing with hot brine reservoirs will be helpful in attacking problems with two-phase miscible fluids. The results of this study will aid the well test group to estimate the capacity of the reservoir.

The petroleum industry uses type curve analysis to predict well performance. These curves are obtained through the solution of a set of partial differential equations, involving pressure vs. time with

different boundary conditions. By matching individual well test data with these type curves, one can obtain information such as permeability thickness, well damage, and reservoir life. The solution of the two-phase flow condition will establish a brand new type curve which can be utilized for prediction purposes. A detailed discussion of this analysis is given in the section concerning software development on well testing and analysis.

## 2. Physical Modelling of Geothermal Reservoirs

Investigators: B. Chen & P. Takahashi

A literature survey has disclosed that there has been very little physical modelling in the field of geothermics. H. R. Henry and F. A. Kahout [73]\* have been conducting related investigations for waste disposal purposes but in their studies the heat source has not exceeded 43°C. The Hawaii model will operate at much higher temperatures. The Stanford University Geothermal Group is also involved with physical modelling [64, 65], although their modelling has been restricted at this time to the active "chimney" portion of the reservoir.

The Hawaii geothermal model will be constructed for the island of Hawaii on a total systems basis; that is, a study designed initially for the actual situation--the entire reservoir bounded on the bottom by an impermeable layer, on the sides by the sea, and on the top by the producing geothermal field and the Ghyben-Herzberg lens--beginning at first with the geothermal reservoir and progressing eventually to the simulation of a fully operating geothermal field. The two initial regions to be investigated will be the Ghyben-Herzberg lens and an element of the porous medium.

Some of the variables requiring consideration in a physical geothermal model are:

- a. permeability--not of the microscopic rock, but of the macroscopic system; that is, fractures will most probably dominate over vesicular or layer porosity in determining permeability,
- b. temperature,

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\* References are listed on pp. 154 to 157.

- c. pressure,
- d. fluid composition,
- e. fluid flow rate,
- f. porosity--to obtain volume fraction.

The size of the physical model and the exact features to be modelled require careful study. If the island of Hawaii is reshaped into a square, each side will be approximately 64 miles in length. (A circular reshape would result in a diameter of 72 miles.) The impermeable bottom layer is generally thought to be at a depth of one and a half miles below sea level. (Note that the ocean floor in the vicinity of the Hawaiian Islands is considerably below this layer.) The permeable medium under consideration is thus 64 miles by 64 miles by 1.5 miles. A physical model on a 64:64:1.5 scale will be of dubious value, as it is the depth dimension that is of greatest interest. It is therefore far more suitable to physically model a portion of the Big Island, rather than the whole island itself, although all areas impacting on the reservoir must be included.

The maximum element selected for the initial study will extend from the lower impermeable layer up to, but not including, the Ghyben-Herzberg lens. The horizontal dimension should be greater than the vertical. As the location of the well will probably be a point several miles inland, a 2:1 ratio appears reasonable with 2:2:1 for a three dimensional model. Figure 3.1-18 is a schematic model of the planned experimental set-up. One face (A) interfaces with the sea. If desired, the heat source can be moved or the size and configuration altered to obtain streamline conditions at the left boundary (B). As the initial analytical model is two-dimensional, with one boundary condition being set by symmetry

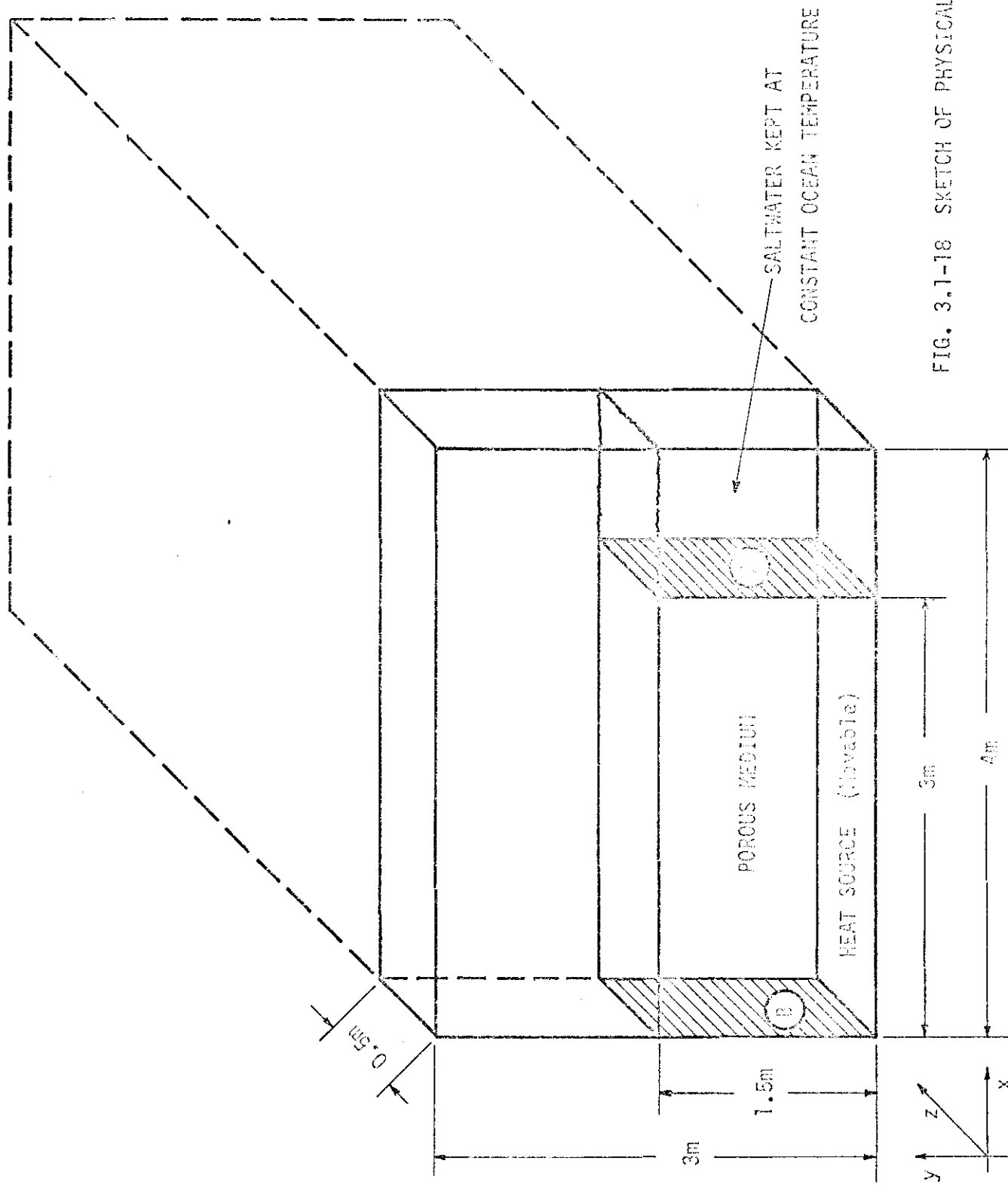


FIG. 3.1-18 SKETCH OF PHYSICAL MODEL

relations, the physical model is being designed accordingly. However, flexibility will be designed into the tank so that conversion can easily be made to a three-dimensional model by increasing the size of the tank in the z-direction.

The minimum element will be a layer of aquifer, with the depth dimension perhaps only several tens of feet. The analysis for this section should be similar to the maximum element.

The preliminary design of the maximum physical model is for a 3-mile wide (from sea to inland boundary) by 1.5 miles deep two-dimensional element. Tentatively, the actual size of the physical model will be 3 meters with the dummy third dimension being 0.5 meters. The height of the tank will be 3 meters to allow for later consideration of different ratios and elements.

The location, configuration and temperature of the heat source must also be specified. There is agreement that magma is generated at the top of the mantle, 20 to 60 miles below the surface of the earth [54]. There will therefore be very large reservoirs of magma at this depth range. There is also agreement that magma reservoirs exist at shallow depths from 1 to 12 miles below the surface of volcanic regions. The shape and size of these shallow reservoirs have been estimated by gravity and magnetic methods to be ellipsoidal or vertically-flattened spheroidal and in the order of 1 to 3 miles along the longer axis [55]. It is expected that one of these magma chambers will provide the large geothermal heat source.

To provide for comparison with the analytical model the heat source will initially be placed at the bottom of the physical model; size,



configuration and actual effective temperature of the heat source will be determined later. For design purposes it will be necessary to allow for flexibility; adequate range (100 to 1200°C), size (from "point" source to plane source), and movability in three directions. The scaling of temperature also needs to be considered carefully.

The exact parameters to be measured and the measuring techniques to be used must be specified. Earlier works in related fields have used probes in a two or three dimensional matrix pattern. Temperature, pressure, flow rate, and fluid composition can be measured using appropriate probes interfacing multi-channel recorders or indicators. The more sophisticated infrared, magnetic, nuclear, electronic (resistance or capacitance), and acoustic (sonic or ultrasonic) techniques will be evaluated for possible use in the Hawaii geothermal model.

Questions related to the porous and fluid media which should be used, whether porosity should match that of the natural rock in the area, and how fissures and/or fractures can be manipulated to obtain the desired permeability remain unanswered at this time. An important problem is the overwhelmingly large scale-down factor involved (1600:1). Dimensional analysis has been used to help determine some of the more necessary scale factors.

In movement of fluid through a geothermal reservoir, the driving force is primarily the buoyant force. This force is created by heat within the geothermal system which decreases the fluid density. The dimensionless number determined to be of prime interest to the study is the Rayleigh Number ( $N_{Ra}$ ). The Rayleigh Number is

$$N_{Ra} = \frac{\rho_s g \beta K (T - T_s) h}{\mu \alpha} \quad (12)$$

(See Equations 4 to 11 for nomenclature).

The literature is sparse on the range of Rayleigh Numbers meaningful to actual geothermal systems. In general the study will investigate the range of  $N_{Ra}$  between 30 and 1000. This will be accomplished by altering the permeability of the solid medium and the temperature of the system. The permeability can be altered by changing the mesh size of the sand or glass bead bed. The temperature change will in turn determine the values of the coefficient of thermal expansion ( $\beta$ ), thermal diffusivity ( $\alpha$ ), viscosity ( $\mu$ ), and density ( $\rho$ ) of the fluid.

All parameters except  $g$  and  $h$  depend upon either temperature or medium used. Permeability is a function of the solid medium. If there is no chemical reaction, it is not a function of the fluids involved. The thermal expansion coefficient ( $\beta$ ), thermal diffusivity ( $\alpha$ ), and kinematic viscosity ( $\mu$ ) are all functions of the fluid and temperature.

The ideal situation is to have a porous medium whose permeability is such that the fluid will not have to be heated above the boiling point to give the desired Rayleigh Number. If it is not possible to find such a porous material-liquid combination, then the system must be pressurized so that the temperature in the liquid can be elevated.

The problem in building a model is to find known materials whose properties are such that their values, when substituted into the Rayleigh Number equation, will give the desired range. Calculations can be made by substituting values for  $\alpha$ ,  $\beta$ , and  $\mu$  of known liquids at various temperatures. Using expected Rayleigh Numbers, a permeability,  $K$ , can be calculated. The substitutions are made into the following equation:

$$K = \frac{N_{Ra} \mu \alpha}{g h \beta (T - T_s)} \quad (13)$$

As the temperature increases,  $\alpha$  increases,  $\mu$  decreases, and  $\beta$  decreases. The results show that as temperature increases, the permeability value is decreased. It can be concluded that the temperature effect on viscosity is the most significant factor in determining the permeability. Further evidence is that, as temperature changes, the values of  $\alpha$  and  $\beta$  do not change as much relative to the change in viscosity. In order to minimize pressurized conditions, a liquid with the lowest possible viscosity and the highest possible boiling point should be used. Water seems ideally suited to these conditions.

Yet another question is whether the vessel should be pressurized or unpressurized. Pressurized hardware systems are several times more expensive than unpressurized ones. Certainly, if pressures approaching ten atmospheres are required, a totally glass-faced siding, which makes observation of streamlines practical, must be abandoned.

The very first test runs will be on an unpressurized basis. The Rayleigh Number for which boiling first occurs in seawater-sand (30-40 mesh) media is 484. As a Rayleigh Number of  $4\pi^2$  or 40 is the point at which convection initiates, a study from 30 to 484 under unpressurized conditions is meaningful. As the sand bed grain size is reduced, permeability decreases, and lower Rayleigh Number conditions can be simulated.

However, there is one overriding reason why the physical model should be made adaptable to pressurized conditions. If a section at depth is modelled, hydrostatic conditions must be simulated. It is therefore recommended that for versatility the model be pressurized. Other specifications are:

Porous media	30-40 mesh sand,
Liquid media	Seawater.

The pressurized vessel will also allow for simulation of porous layers located at great depths.

The plan of attack will involve the following:

- a. a proper range of Rayleigh Numbers for the Hawaii geothermal system will be verified,
- b. model specifications will be determined to give the Rayleigh Number range,
  - 1) type of porous media (permeability),
  - 2) type of fluid,
  - 3) temperature range,
  - 4) need for pressurization.
- c. building a model,
  - 1) determining the proper scales,
  - 2) determining the type of heat source,
  - 3) determining the devices for measuring the various parameters.
- d. testing a model,
- e. simulation studies,
- f. modification of model,
- g. interfacing with Ghyben-Herzberg physical model.

The present plan is for simulation of steady-state conditons where an infrared technique is used to map temperature profiles and a yet undetermined measurement scheme is used to obtain streamline patterns. There is a possibility that at least a partial glass face will be designed into the vessel to enable observation of streamlines.

### 3. Well Test/Analysis

Investigators: B. Chen, L. S. Lau, & P. Takahashi

There are several phases to this portion of the investigation. A logical breakdown is following the "life" of a well.

- a. There must be initial and continuing coordination with the geophysical drilling program to ascertain that the important parameters are measured while the hole is being drilled. These measurements are mainly geophysical logs; as for example, those that depend on resistivity, sound, and radioactivity. (Details are provided in an earlier section).
- b. After the well is completed, downhole measurements must be taken. (Again, details are provided in an earlier section).
- c. A general program of well testing must be planned to determine the ultimate producing capacity and optimal producing rate of the geothermal field. One example is to coordinate a series of interference tests to detect connectivity.
- d. After the well tests are made, the data must be analyzed so that well performance and resource availability can be predicted.
- e. A set of type curves to analyze non-isothermal flow conditions must be developed.
- f. A set of type curves to analyze two-phase flow conditions must be developed.

## TASK 3.1 GEOTHERMAL RESERVOIR ENGINEERING

### I. Numerical Modelling of Geothermal Reservoirs

#### A. Timetable

August 15, 1973

1. Survey of literature on the Ghyben-Herzberg lens dynamics with emphasis on coning and steady flow with heat source below
2. Survey of literature on building a physical model to simulate the Ghyben-Herzberg lens system

December 31, 1973

1. Formulation of the convection problem for a rectangular porous region
2. Finite Difference solution of the convection problem for a rectangular region
3. Formulation of the coning problem

May 31, 1974 .

1. Completion of the problem of free convection in an unconfined geothermal reservoir
2. Completion of the investigation of the effect of vertical heat source on the upwelling of the water table
3. Completion of the survey of literature on the numerical solution of pumping and re-injection in an aquifer under isothermal conditions

December 31, 1974

1. Completion of the numerical solution of steady state pumping and reinjection in a confined geothermal reservoir
2. Formulation of the finite element solution of free convection in a geothermal reservoir with irregular geometry

May 31, 1975

1. Completion of the investigation of the effects of geothermal heating on Ghyben-Herzberg lens
2. Completion of the numerical solutions for heat transfer and fluid flow characteristics in an axisymmetric geothermal reservoir
3. Completion of the finite element solution of free convection in a two dimensional geothermal reservoir with irregular geometry

December 31, 1975

1. Completion of the investigation of transient responses in geothermal reservoirs with pumping and reinjection
2. Refinement of the finite element computer code to take into consideration of various effects

## Well Test/Analysis & Physical Modelling

### A. Timetable

May 19, 1973	1. Research on gas petroleum well test/analysis
June-July-August, 1973	1. Research on the nature of a geothermal reservoir and geothermal well testing
July-August, 1973	1. Initiation of a international survey on the state of Geothermal Reservoir Engineering
August 31, 1973	1. Further research on reservoir and well test/analysis 2. Preliminary analysis of international survey
December 31, 1973	1. Research on the construction of a geothermal reservoir model 2. Preliminary system design of a physical model 3. Further research on geothermal reservoirs and well testing (with Geophysics) 4. Investigation to determine whether a typical Hawaii geothermal reservoir is an open or a closed system
May, 1974	1. Assessment of well test hardware 2. Completion of analysis on international survey 3. Preliminary design of physical geothermal reservoir model 4. Further research on geothermal reservoirs and well testing (with Geophysics)
December, 1974	1. Selection of hardware for well testing 2. Assessment of software for well testing 3. Completion of initial phase of the fabrication of the physical model
May, 1975	1. Purchase of hardware and selection of software for well testing (with Geophysics) 2. Initiation of laboratory parametric checks on physical model 3. Assessment of methods for measurement and analysis of two-phase flow 4. Preliminary design of Ghyben-Herzberg Lens physical model and consideration of interfacing problems

December, 1975

1. Initiation of laboratory simulation studies
2. Construction of Ghyben-Herzberg physical model
3. Purchase equipment to interface the different physical models

May, 1976

1. Analysis of laboratory simulation runs and correlation with computer model
2. Interfacing of physical models into a general model of a geothermal field
3. Development of methods for two-phase flow measurement and analysis
4. Measurement of temperature, pressure and flow rate--both downhole and at wellhead
5. Preliminary analysis of data

December, 1976

1. Final analysis of geothermal well data
2. Prediction of geothermal field performance



### TASK 3.6 OPTIMAL GEOTHERMAL PLANT DESIGN

Investigators: H. C. Chai, J. Chou, & D. Kihara

#### 1. Conceptual Design of a Research-oriented Plant

One of the objectives of the Hawaii Geothermal Project is to plan and design a research-oriented, geothermal power plant in the megawatt range. Specific plant design cannot be begun until the geothermal energy source has been located and tested; however, study of the characteristics of different plant systems can be initiated in preparation for the specific design later. It is envisaged that the research-oriented plant may consist of more than one type of system and must be easily adaptable to any changes.

The vapor-flashing system, successfully used in New Zealand and Mexico, is being studied at the University of Hawaii. The current study includes the optimization of operating procedures of vapor-liquid separators, design of cyclone separators, pressure-drop of two-phase flow in pipes and heat rejection equipment. After this year, the geothermal research team in Hawaii should have sufficient knowledge in mechanical design of a vapor-flashing system for a research plant. Hopefully, some new approaches will be found for improving the current designs of the components.

Another method of generating power from hot brine is the use of a binary fluid system in which hot brine is forced through a heat exchanger to prevent flashing and to transfer its energy to a working fluid such as isobutane. In the current study, it has been determined that the performance of the basic binary system can be greatly improved by the addition of a regenerative heat exchanger. The regenerative binary system can be particularly useful to industrial applications such as forest-products processing, sugar processing and desalination of salt

water, where the needs of power and low-temperature heat exist simultaneously. The proposal is to make an extensive study of the designs of the components, to investigate different working fluids and to make economic projections of the regenerative binary system. A comparison of the regenerative binary system with a multiple-stage vapor-flashing system will be made regarding the selection of the most appropriate system for a particular set of conditions.

Although efforts will be focused on the evaluations, designs and specifications of the regenerative binary systems, some attempts will be made to search for new systems and to keep informed on equipment and systems under investigation by others. The ultimate purpose of the research-oriented plant is to prove new concepts in design, not restricted to those originated locally, and to test new equipment for the advancement of geothermal power engineering.

An experienced engineering firm with proven competence in geothermal power plants will be engaged to provide consulting services in the design and construction of the proposed research-oriented power plant. During the calendar year 1975, these consulting services will include a conceptual design and cost estimate of the power plant. This conceptual design will incorporate the research goals submitted by personnel of the Hawaii Geothermal Project; e.g., in-plant verification of laboratory heat exchanger tests, testing of proposed improvements in designs of components, and in-plant proving of new technology in geothermal plant components.

## 2. Heat Exchanger Design

According to the literature survey made during the past year, correlation equations which predict boiling heat transfer rate and pressure drop of two-phase flow for a single tube are available. However,

there is practically no information available on boiling heat transfer and pressure drop for tube bundles. Therefore, it is proposed to design and construct horizontal and vertical heat exchangers to study the boiling heat transfer and pressure drop characteristics of the heat exchangers.

The major effort will be put on the horizontal heat exchangers because of the simplicity of the horizontal arrangement for very long tubes and the ease in cleaning the tubes after fouling by the passage of hot liquid inside.

In this experimental work, Freon-11 will be used as the working fluid because of its low vapor pressure and safe operational characteristics. The Freon-11 will be boiled on the outside surface of electrically heated tubes. A schematic diagram of the heat transfer loop is shown in Figure 3.6-6.

#### Horizontal Heat Exchangers

The correlation equations available for a single horizontal tube cannot be used for the design of the heat exchangers. The bubbles formed on a tube agitate the fluid and affect the heat transfer rate of the adjacent tubes of the heat exchangers. Furthermore, the bubbles formed on the tubes in the lower rows of the heat exchangers rise to the upper rows, agitate the fluid, and affect the heat transfer rate of the tubes in the upper rows. Therefore, in the design of the horizontal heat exchangers, either a new correlation equation must be formulated, or a correction factor must be determined and applied to the correlation equations for single tubes.

Initially the heat exchangers will be built with only one row. Tube spacing in the row will be varied to study the effect of tube



spacing on the average heat transfer coefficient. Also, the minimum tube spacing which will not affect the heat transfer coefficient of adjacent tubes will be determined for different fluid inlet conditions such as quality of vapor and flow velocity.

Following this study, a proper tube spacing will be selected, and heat exchangers will be built with one to six transverse rows to study the effect of number of transverse rows on the average heat transfer coefficient.

The investigation will be made for both pool boiling and flow boiling. Some of the technical data for the heat exchangers are as follows:

outside diameter of tube	0.315 inch and 0.406 inch
tube length	24 inches
tube material	copper
transverse pitch	1.25D, 1.50D, 1.75D, 2.0D, 3.0D, 4.0D & 5.0D (D: tube outside diameter)
maximum heat input	100 watts per square inch
inlet quality	0 -- 70%
flow velocity	3 -- 15 fps

#### Vertical Heat Exchanger

A vertical heat exchanger of the following dimensions will be built:

outside tube diameter	0.406 inch
tube length	48 inches
tube material	copper
approximate tube pitch	1.5D (D: outside tube diameter)

number of tubes . . . . . 12 arranged in a  
regular hexagonal  
pattern

shell inside diameter . . . . . 3.72 inches

Experiments will be performed under various conditions, and the results obtained will be compared with the performance predicted by the computer program for identical conditions. The correlation equations used in the computer program are for the boiling inside vertical tubes. In the computer program these equations are applied to boiling outside vertical tubes by using the equivalent hydraulic diameter of flow channel. The validity of this application will be checked by this experiment.

#### TASK 3.5 REFERENCES

1. Henson, Alf, "Thermal Cycles for Reciprocating Cycles and Turbine Installation at the Stevens Power Plant, California," A.S.M.E. JOURNAL OF HEAT TRANSFER, OCT. 1961, Trans. Vol. 83, pp. 365-379.
2. Kern, W. H., HEAT-TRANSFER DESIGN, McGraw-Hill Book Co., 1958, p. 173.
3. Chen, John C., "Correlation for Boiling Heat Transfer to Saturated Fluids in Convective Flow," JOURNAL OF HEAT TRANSFER, Vol. 80, pp. 323-329, 1958, A.S.M.E. JOURNAL, Vol. 80, No. 3, July, 1958, pp. 323-329.

### TASK 3.6 OPTIMAL GEOTHERMAL PLANT DESIGN

#### A. TIMETABLE

- |                    |  |
|--------------------|--|
| March 31, 1975     | <ol style="list-style-type: none"><li>1. Establish the general requirements, ground rules, and design criteria of the research-oriented plant for liquid-dominated geosites.</li><li>2. Construct horizontal heat exchanger and write generalized computer program for horizontal heat exchangers.</li></ol> |
| June 30, 1975      | <ol style="list-style-type: none"><li>1. Set up the procedure for the design and selection of the components of regenerative binary fluid plants.</li><li>2. Test horizontal heat exchanger and refine computer program. Start construction of vertical heat exchanger.</li></ol>                            |
| September 30, 1975 | <ol style="list-style-type: none"><li>1. Lay out the basic flow diagram of the plant based on a regenerative binary fluid system with a water flashing cycle as an alternative.</li><li>2. Analyze test data for horizontal heat exchanger and begin testing of vertical heat exchanger.</li></ol>           |
| December 31, 1975  | <ol style="list-style-type: none"><li>1. Estimate the capital costs of the plant, evaluate the unit of netting cost, and compare the feasibility of the two cycles.</li><li>2. Test and analyze test data for vertical heat exchanger.</li></ol>   |

### TASK 3.0 ENGINEERING COORDINATION AND SUPPORT

Personnel: P. C. Yuen & I. H. Sato

The Engineering Program consists of two research tasks: (1) Task 3.1 which is concerned with problems below the earth's surface, and (2) Task 3.6 which is concerned with problems above the surface. Task 3.0 Engineering Coordination and Support will provide support services for the research personnel of the two tasks and coordinate the work between the tasks and among the programs in the Hawaii Geothermal Project.

Typing, secretarial, and clerical assistance will be provided by personnel of Task 3.0 for correspondence and for the preparation and reproduction of reports, journal articles, and other publications. A library of pertinent books, journals, reports, and records will be maintained. The processing of payrolls and purchase orders as well as the keeping of fiscal records will be a responsibility of Task 3.0.

In order to coordinate the research in the Engineering Program, the Principal Investigator will meet regularly with task leaders and with other project personnel to discuss their work, and to plan future work. The Principal Investigator will also meet regularly with his counterparts in the Geophysical Program, the Environmental and Socioeconomic Program, and the Drilling Program, as well as with members of the Management Team, to coordinate the work of the Project.



#### CURRENT RESEARCH SUPPORT FOR PRINCIPAL INVESTIGATOR

The following is a listing of the extramurally-funded projects for Paul C. Yuen, Principal Investigator of the Engineering Program.

1. An Engineering Feasibility Study of an Ionospheric Technique to Improve Tension Warning Systems  
National Science Foundation, Grant GI-34973
2. The Continuation of a Study of coupling Mechanisms which Produce Ionospheric Variations from Solar and Terrestrial Events  
National Science Foundation, Grant GA-23964
3. Ionosphere Studies Using Total Electron Content  
National Science Foundation, Grant GA-17330

VITAE AND BIOLOGRAPHIES FOR  
ENGINEERING PROGRAM

(Proposed program for January 1 - December 31, 1975)

## Environmental-Socioeconomic Program

### Generally

Two basic interests underlie this portion of the Hawaii Geothermal Project. One is to ascertain the impact of geothermal power production on the economy and social order of the State, particularly on land use, economic growth and diversification, cost of living, employment, population growth and its spatial distribution. The analysis takes into account changes in legislation, public utility regulation and development planning necessitated by this new source of energy in Hawaii; it considers how applicable the experience of this state would be to other areas of the U.S., including its Pacific Territories.

The second interest is to estimate how to minimize possible adverse effects of geothermal development on the environment and local ecosystems. This interest is interlinked with the first, since Hawaii's economy is already heavily dependent on tourism and appears to attract more scientific research centers, and both these activities are enhanced by protection of the natural environment.

The 1973-74 national energy shortage is being felt with special force by Hawaii, which has not developed in significant quantity any energy sources alternative to oil.\* Consequently, public and governmental interest in geothermal energy has deepened considerably since this project began in May 1973. It is now looked to as a possible means of reducing the state's virtually complete dependence on oil imports and as a potential source of new jobs in a presently

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\*On a few of the Hawaiian Islands, small hydroelectric plants and steam obtained by burning cogasse at sugar mills provide marginal sources of energy for the local electric companies.

stagnant local economy. (The level of unemployment in the State of Hawaii rose to an average of 7% in the first quarter of 1974 and remained there into June.) One of the uses of the research conducted under this program is to set reasonable limits to these expectations, assuming that geothermal resources of commercial value are discovered.

#### Program by Major Tasks

##### Task 4.0: Program Support

Support services and coordination will be provided for the four line tasks involving 12 faculty members, four students and two consultants who will be participating in the Socioeconomic-Environmental Program. Communication with the appropriate State of Hawaii and County of Hawaii officials concerned with the legal, regulatory, planning and environmental aspects of geothermal development will continue to be maintained.

##### Task 4.1: Environmental Aspects

The key event affecting the timing of this task is the drilling of holes for geothermal exploration. Of particular concern is drilling that will penetrate through the Geyser-Kamoharui lens. Both the "intermediate" holes averaging 2,000 feet in depth and the "deep" holes which will be approximately 6,000 feet deep fall into this category. It is presently estimated that the drilling of the "intermediate" holes will begin during the summer of 1975. The "deep" holes are scheduled for commencement of drilling during the spring of 1976.

Baseline studies on the chemical, physical and biological characteristics of the lens will be evaluated through tests conducted on the "shallow" wells that will penetrate to the lens. It is possible that constituents of the underlying water such as salinity, entrained gases and nutrients degrade the lens through ver-

tical mixing within the shaft and lateral diffusion into the porous volcanic rock substrate. Baseline data on the lens, obtained through studies on the "shallow" wells in conjunction with careful monitoring to detect any changes in the lens during the drilling of "intermediate" and "deep" wells are thus essential. Drilling sites that are considered vulnerable to significantly adverse effects on the Ghyben-Herzberg lens will be avoided. It is anticipated that the drilling will have a minimal impact on the surface environment. However, the laying of road is necessary for mobilization of the drilling rig and related equipment might have a significant impact. Therefore, baseline studies will be required prior to any road construction. These baseline studies will include the characterization of flora and fauna and the identification of any significant archaeological sites within the three proposed drilling areas, with greatest emphasis on possible road corridors and potential "deep" well sites. The archaeological investigation will be led to by a specialist in pre-Cook Hawaiian history in consultation with the Bishop Museum. Unique Hawaiian ecosystems, rare and endangered species and important archaeological sites will be avoided. Other sites of significant but lesser ecological or archaeological importance will be avoided if possible; economic considerations, notably potential for geothermal energy and access will have to be given full consideration.

Results of these baseline studies will also provide information for preparation of environmental impact statements, if required, for proposed road construction and "intermediate" and "deep" well drilling.

A further use of the aforementioned studies will be to assess the potential environmental impact of the construction and operation of energy generating facilities, assuming one or more of the "deep" test holes provide the necessary geothermal source. Additional environmental baseline studies dealing with air quality and meteorological conditions will also be required for this purpose. Gases,

such as  $H_2S$  and ammonia that might be entrained in the geothermal energy source, may be liberated in significant amounts into the atmosphere upon being brought to the surface. If so, they will be studied to assess the impact of gas liberation on local ambient air quality and of any possible deleterious effects on flora and fauna. If cooling towers are required, the meteorological investigations will also provide essential data on the possible impact of the towers on local weather.

If it appears that deep ocean water may be used as a coolant for geothermal power production, the baseline studies will be extended to this portion of the environment, examining the ocean at the sites indicated by the geological and engineering teams to be likely sites for cold water intake and warm water discharge.

The baseline studies will be conducted under the direction of the Environmental Center of the University of Hawaii.

#### Task 4.2: Land and Environmental Aspects

During the last half of 1978, researchers in this task invited to informal discussions at the University representatives of the State and County agencies most directly concerned with geothermal development -- the Department of Land and Natural Resources, the Office of the Attorney General, the Department of Planning and Economic Development and the Department of Regulatory Agencies, all of the State, and the Department of Business and Development of the County of Hawaii. From these meetings there was developed a bill to establish a legal regime for geothermal resources in Hawaii, that is, to define geothermal resources and determine their ownership. The bill was redrafted by the Department of Land and Natural Resources and introduced as part of the administration's legislative program.

To aid the legislators and others concerned with providing a legal basis for this new potential resource, the Hawaii Geothermal Project prepared a report on the Legal and Policy Studies for Geothermal Resource Development in Hawaii. The report summarized the status of federal and state law bearing on geothermal deposits and discussed other law cases in Hawaii which may be pertinent. It took no position with respect to private or public ownership of the subsurface resource, but did indicate that once the issue of ownership was resolved the uncertainty would inhibit utilization of any geothermal fields which may be discovered.

The 1974 Hawaii Legislature subsequently passed a bill (H.R. 2197-74) to establish a Geothermal Region for Geothermal Resources in Hawaii. For legal purposes, defining them as a well within the definition reserving title or property of the State government. The law, signed by the Governor in June 1974, is brief and leaves little or no question of geothermal production to the State Department of Land and Natural Resources.

A preliminary draft of possible regulatory provisions has been prepared for the project by David Anderson, Assistant Attorney General of the State of California. The draft will be worked over with the Hawaii Department of Land and Natural Resources, which has administrative responsibility for all "mineral" resources of the state, but no experience with geothermal energy. It is anticipated that some of this work will possible clarification would come to the two geothermal sites in 1975, when the State Legislature meets in regular session.

In mid-1974, assuming that initial indications from the drilling are not strongly negative, the work will be extended to working with the State Department of Regulatory Agencies concerning the rules and procedures of public utility

regulation which would be applicable to geothermal steam production and distribution. If positive test results or other factors lead the Department to the conclusion that it was premature to consider how it would regulate the economics of geothermal steam operation, then this portion of the task would be deferred.

#### Task 4.3: Land-Use and Planning Aspects

After potential sites for drilling geothermal wells are identified, this task will identify the owners of the sites -- whether public agency or private holders -- and help negotiate with the owners or managers of the land for permission to drill.

Over the entire sequence of geothermal exploration, drilling and production, the project will work with government officials who may be involved in planning and zoning of geothermal areas and in the vicinity of the wells. Consultation with both levels of government will be necessary to ensure that there are no barriers to development imposed by land-use laws. As geothermal resources are identified, the State Planning and Economic Development and the House of Representatives, Department of Research and Land Development will be informed, so that the development plans of both levels of government can be modified to take these new resources into account. Liaison with the State Department of Land and Natural Resources, the designated administrator of state-owned geothermal resources, will be maintained.

#### Task 4.4: Literature

During Phase I of the Inland Geothermal Project we prepared an annotated bibliography on Geothermal Power Economics, with more than 100 items. Utilizing this bibliography, we began to compile an inventory of geothermal production



units around the world, simplifying production and cost data. This data will be used to set some of the parameters for modeling economic impact projections for geothermal development on the Island and within the State of Hawaii. To this same purpose, the best estimates of the costs of alternative energy sources for Hawaii -- oil, nuclear power and solar energy -- are being gathered.

A study of energy use on the Island and in the State of Hawaii, projected to approximately 1980, has been begun and will be completed by the end of 1975. It will estimate the potential impact of geothermal power production -- at several assumed levels of energy availability -- on the Island economy. The study will cover the following: 1) power substitution into it (i.e., the result of substituting geothermal power for oil in the production of electricity); industrial production (the part of the economy, commercial and industrial, that is self-sufficient in energy); 2) the impact of geothermal substitution on energy cost, prices, population distribution, and other public resource values.

In this study, development of geothermal resources of Hawaii County and Hawaii State will be studied at least over a decade to allow evaluation of the exploitation of existing fields. It is scheduled for the first half of 1976. Also projected is a narrative on hydrothermal manifestation of geothermal resources development, adopting a Hawaiian feasibility model initially applied to the field of petroleum exploration.

The study will also address the strategy of economic development on the basis of geothermal resources, considering the comparative roles of public and private investment. The problems of the Hawaii case, and the elements of the economy not so much common to other areas of the United States, will be noted so that the transferability of this analysis can be seen.

As the technology of utilizing geothermal resources as they may occur in

When it is worked out, the location program will furnish consultation on economic aspects of well location to the drilling program and on the economic aspects of plant design to the Engineering program.

QUEST 1. RESEARCH SUPPORT FOR AN ALLOWED INVESTIGATOR

The following is a listing of all grant-funded projects for Robert H. Kinsler, Principal Investigator of the Environmental and Socio-economic Program.

None.

VITAE AND BIBLIOGRAPHIES FOR  
ENVIRONMENTAL-SOCIOECONOMIC PROGRAM

Preliminary Proposal Exploratory Research Drilling  
Island of Hawaii

Agatin T. Abbott

Abstract

The search for a geothermal energy source on the island of Hawaii under the current NSF program began in March 1973. Between that date and the present a large amount of data has been gathered particularly along the East Rift Zone of Kilauea (Puna Rift) in the fields of geophysics, engineering, and legal-socio-economics. The project has reached a stage where these various lines of study must converge to provide information for the exploratory drilling. The drill is the only tool that will conclusively indicate whether a potential source of geothermal energy lies beneath the surface. The drill holes will serve as an exploratory tool and are not intended to serve as production wells unless of course a geothermal source might by chance be tapped.

Three areas are selected as being most favorable for exploratory drilling. These are the East Rift of Kilauea, the Southwest Rift of Kilauea, and the Southwest Rift of Mauna Loa.

Within each of these areas it is proposed to drill 8 shallow water well type of holes of an average depth of 500 feet, 4 holes to 2,000 feet and one hole to 6,000 feet or more. This accounts for approximately 11,000 feet of drilling per area or approximately 54,000 feet of total drilling in the project. It is estimated that this complete drilling program requires a period of at least two years and eight months. The Site Selection and Operations Committee reserves the right to make the final decision on drill hole

location, depth, and diameter. The committee is also charged with the responsibility of deciding on the types of down hole measurements to be made, by whom and how often. The general operational plan for the drilling rests with the committee in consultation with the company designated as the Drilling Program Manager.

This proposal is submitted in a preliminary form because at this date no drilling contract have been let. There will undoubtedly be revision of cost figures by the engineering company when the drilling contractual arrangements are completed.

## Preliminary Proposal for Research Deep Hole Exploratory Drilling

Agatin T. Abbott

### INTRODUCTION

As the various avenues of research and exploration which have been described earlier in this report are being completed or are in various stages of completion, it becomes clear that the next logical step in the search for geothermal energy on the island of Hawaii is to test beneath the surface by drilling.

At this time three areas on the island of Hawaii have been selected as being the most promising. These are the East Rift of Kilauea (Puna Rift), the Southwest Rift of Kilauea, and the Southwest Rift of Mauna Loa. According to the present plan exploratory drilling will be undertaken in those areas in the order in which they are mentioned above.

### PREVIOUS WORK

The drilling program is based on the results of a number of other lines of investigation and research that have been carried out during earlier stages of the Hawaii Geothermal Project. Reference is made to tasks under Phase I Geophysics, Tasks 2.1 Photogeologic; 2.2, 2.4 Electromagnetic; 2.3 Electrical Resistivity; 2.5 Microseismic. Reference is also made under Phase I Extension Geophysics, Tasks 2.1 Preparation for Exploratory Drilling, 2.2 Geoelectric, 2.3 Gravity and Magnetic, 2.4 Thermal, 2.5 Microseismic, 2.6 Geochemical. Under Engineering Task 3.1 Reservoir Engineering, and under Environmental-Socioeconomic, Tasks 4.3, 4, 5 Legal and Planning. Most of the preparatory effort has been concentrated in the Puna area. The other two areas are being studied this summer.

A large amount of information is contained in earlier works on the geology and groundwater hydrology of portions of the island of Hawaii, that was not done for the express purpose of gaining geothermal information. These references are provided at the end of this chapter.

## PERSONNEL

Because the exploratory and research drilling program of the Hawaii Geothermal Project is very large, both in terms of financial involvement and also in terms of the fields of interest that it encompasses, the personnel to manage this phase is as follows:

Co-principal Investigator and Director of Exploratory Drilling -

Agatin T. Abbott, Geology and Management

University of Hawaii

Site Selection and Operations Committee

Agatin T. Abbott - Geology, Univ. of Hawaii

Pow-Foong Fan - Geochemistry, Univ. of Hawaii

Augustine S. Furumoto - Geophysics, Univ. of Hawaii

Gordon A. Macdonald - Geology, Univ. of Hawaii

Donald Peterson - Geology, U.S. Geol. Survey

Charles Zablocki - Geophysics, U.S. Geol. Survey

The role of the Site Selection and Operations Committee is a decision making one regarding all phases of the drilling program and integration of the drilling program with other phases of the HGP such as Geophysics, Engineering, and Legal and Socio-economics. There must be a close association between the several fields of interest in this project, if the maximum benefit is to be achieved from the holes drilled.

In order to have as large an input as possible from knowledgeable persons who are in one way or another concerned with geothermal energy, a large body



of advisors has been invited to contribute ideas and suggestions as the project continues. There will undoubtedly be additional names added as time goes along, but at the present time the following persons comprise the Advisory Group:

David Anderson - State of California Resources

Kenneth Brunot - National Science Foundation (formerly Phillips Petro. Co.)

Dan Davis - U.S.G.S.

Robert Kamins - University of Hawaii

Douglas Klein - University of Hawaii

George Keller - Colorado School of Mines

George Kennedy - University of California, L. A.

Kost Pankiwskyj - University of Hawaii

Henry Ramey - Stanford University

Robert Rex - Republic Geothermal Company

Fred Smales - Hawaiian Cement Company

Harold Stearns - U.S.G.S., retired

Robert Tilling - U.S.G.S.

John Unger - U.S.G.S.

Donald White - U.S.G.S.

George Woollard - Hawaii Institute of Geophysics

Paul Yuen - University of Hawaii

#### DRILLING MANAGEMENT

It is the opinion of the Site Selection and Operations Committee that the most effective and in the long run the least costly system of managing the drilling operations is to employ a professional engineering firm and delegate to it the responsibility of handling contracts, sub-contracts, bids, drilling procedures, down hole measurements, safety regulations, leases, clean-

up specifications and a host of related arrangements that can much better be managed by a professional firm than by the personnel of the Hawaii Geothermal Project.

The decisions on such matters as location of the holes, number of holes, types of scientific measurements to be made, coring procedures depth or termination of a hole and similar matters relating to the gathering of scientific and technical data and the assessment of their results will rest with the Site Selection and Operations Committee.

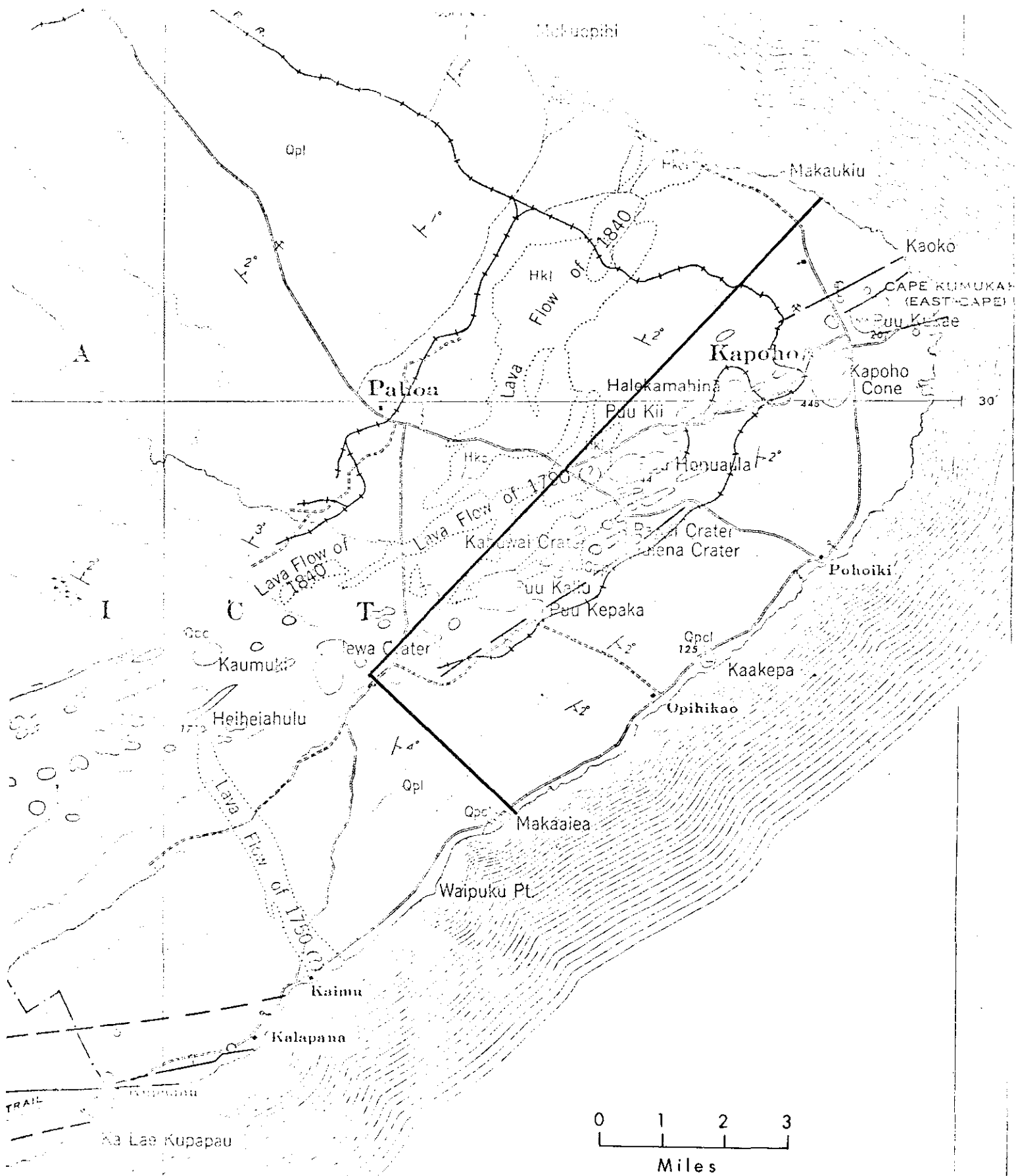
It will be the responsibility of the Site Selection and Operations Committee to choose the engineering firm that will assume the job of Program Management for the drilling.

## PLAN FOR EXPLORATORY RESEARCH DRILLING

### 1. East Rift of Kilauea

At the present time of planning the drilling program encompasses three types of holes: (1) shallow holes (average depth - 500 feet) for water samples and temperature measurements. (2) intermediate depth holes (2000 feet) for temperature measurements, rock alternation, water chemistry. (3) deep hole (6,000 feet or more) to try to reach a potential geothermal source and for deep hole data.

The rationale on the drilling of exploratory holes to 6,000 feet or deeper is that if there exists volcanic heat at those depths the hydrostatic



Approximate Boundary of Area Considered  
for Exploratory Research Drilling in Puna District,  
Island of Hawaii. (map after Stearns & Macdonald,  
1945)

pressure of the overlying ocean water at depths of 6,000 feet or more water temperatures could reach over 400°F in the peripheral areas of a volcanic heat source. Under a hydrostatic head of 6,000 feet there would be no surface manifestation of the submerged hot water zone. It is this type of environment that the deep drilling is attempting to discover.

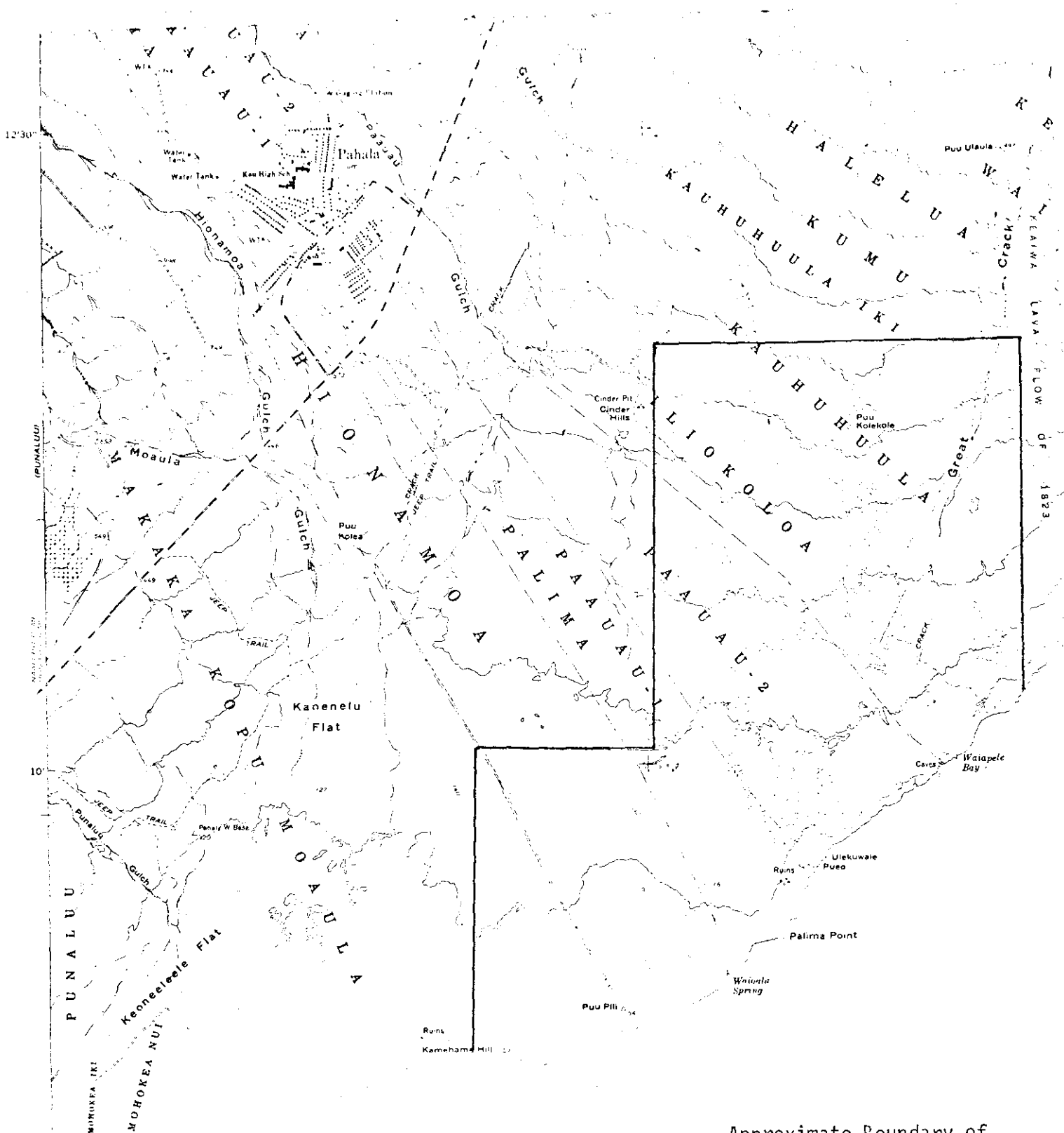
The East Rift of Kilauea is perhaps the best known of the three areas under consideration. It contains a number of drilled wells, and is the scene of considerable activity by real estate sub-dividers. It has been studied intensely over the years by scientists of many disciplines.

Measurement of water temperatures and water chemistry has been completed in most of the accessible wells in the Puna District (See report by Dr. Pow-Foong Fan). The geophysical data is included in earlier reports for the HGP. Self potential survey is presently underway (see report by Dr. Charles Zablocki).

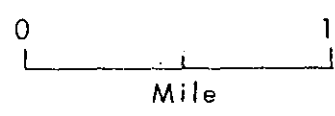
No specific sites for drill holes are shown in this proposal because the field data are still incomplete. When as much data as possible within a reasonable length of time have been assembled (probably the end of the summer), the Site Selection Committee will designate sites for the proposed drill holes. The shallow hole locations will be decided first, and then depending on the information gathered from them plus all other information the intermediate depth holes will be spotted. Depending then on the results obtained in the intermediate holes, the decision regarding the location of the principal hole to a depth of 6,000 feet or more will be made.

## 2. Southwest Rift of Kilauea

The Southwest Rift of Kilauea is not really so well known from the standpoint of geology, geophysics, or groundwater hydrology as the East Rift. It is an uninhabited lower portion of the Kaū desert and contains few roads and one or two trails.



Approximate Boundary of.  
Area Considered for Exploratory Research  
Drilling in Vicinity of Great Crack, Island of Hawaii



The principal indication of thermal anomalies at this time are those of the infrared scanning surveys. Geophysical surveys will be conducted in the area during the summer. IR imagery is in part reacting to surface texture.

The same sequence of drilling is planned for this area as for the Puna district, i.e. shallow holes first, followed by intermediate depth holes, and then a deep probe to 6,000 feet or more.

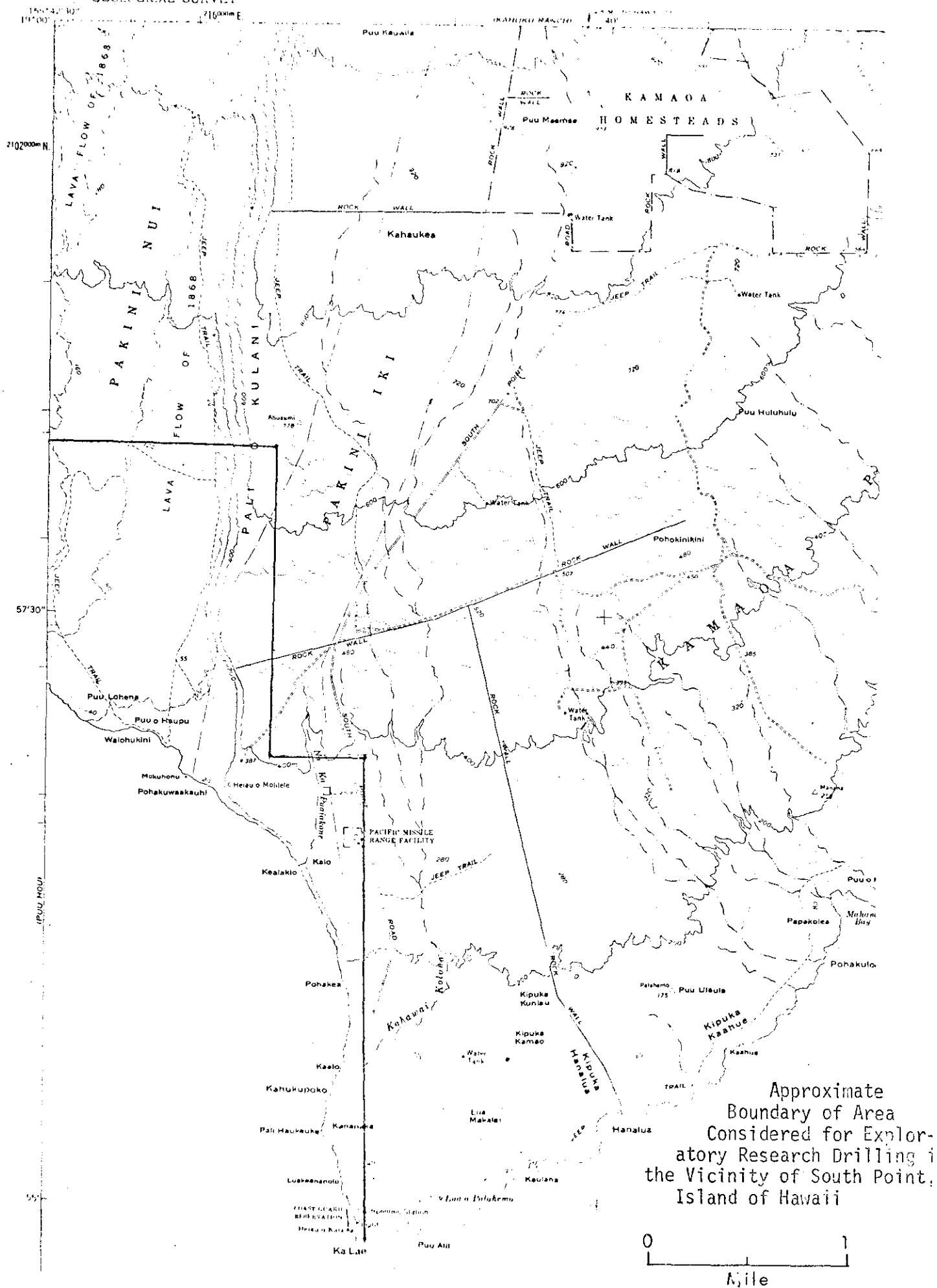
### 3. Southwest Rift of Mauna Loa

Plans for drilling in the lower portion southwest rift of Mauna Loa are still tentative. Infrared scanning results indicate a possible temperature rise along certain sections of the Kahuku fault scarp. The infrared results may be influenced by cliff steepness or texture of broken rock along the base of the pali. A body of warmer ocean water is also indicated offshore.

On the other hand the Kahuku fault is a major structural feature and probably extends to great depths as well as extending for over 25 miles on the surface and under the ocean. Even though the infrared may be reporting effects other than temperature the Southwest Rift still appears to hold a certain amount of promise as a major structural feature, that could influence heat flow from depth.

No geophysical results are available at this time for the South Point area. Geophysical surveys are planned during the summer of 1974.

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### General

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## Geology and Ground-water Hydrology

by Gordon A. Macdonald

### INTRODUCTION

The island of Hawaii is formed by five major volcanoes. Kohala, at the north end, and Mauna Kea, next to the south, have not been active in historic time, and the last eruptions took place several thousand years ago. On the west side of the island, Hualalai erupted last in the years 1800-1801. Since the advent of European and American visitors to Hawaii and the beginning of written records, Mauna Loa and Kilauea have been among the world's most active volcanoes. Mauna Loa erupted last in 1950. Kilauea has erupted repeatedly since 1952, and has been in eruption almost continuously since 1969.

Both Kilauea and Mauna Loa are indented by summit calderas, whose floors are as much as 180 meters below the rims. The calderas were formerly somewhat deeper, but have been partly filled by lava flows. As exposed in the dissected calderas of older volcanoes on other Hawaiian islands, the lavas filling the caldera tend to be considerably denser, more massive, and less permeable than those on the flanks of the volcano outside the caldera. In some of them, such as the Koolau caldera on Oahu and the East Molokai caldera, further reduction in permeability has resulted from alteration of the rocks by gases rising through them, with transformation of pyroxene to chlorite and epidote, and deposition of secondary quartz, calcite, and zeolites in vesicles and other openings. Similar changes can be presumed to have occurred, at least to some extent, beneath the caldera depressions of Kilauea and Mauna Loa.

Extending outward from the calderas are rift zones--zones of innumerable open or filled fissures that have served as pathways for the rise of the magma that produced most of the eruptions. (A few eruptions take place away from the rift zones.) Kilauea and Mauna Loa each have two major rift zones. At the surface the rift zones are marked not only by fissures, but also by many spatter cones and ramparts and cinder cones built at the site of eruptions, and by a few pit craters. Parts of the rift zones are bordered by faults, between which the intervening area has sunk to form a shallow graben. Similar rift zones exposed by erosion on older Hawaiian volcanoes contain thousands of dikes, formed by consolidation of the magma in the fissures. Individual dikes may reach as much as 15 m in thickness, but most of them are less than 5 feet. Transects of the dissected rift zones typically give counts of several hundred dikes per kilometer, and more than 350 per kilometer per mile of width of rift zone is not uncommon. The attitude of the dikes varies considerably, but most of them strike more or less parallel to the rift zone and dip in other direction at angles greater than  $70^{\circ}$ .

Between the dikes there remain many slices of basalt lava flows. The inter-dike lava-flow masses consist of both pahoehoe and aa flows, generally thin bedded, and identical to those on the flanks of the volcano away from the rift zones. For the most part they are moderately to highly permeable. The openings primarily responsible for the permeability are joints, inter-flow spaces, openings between the fragments in aa clinker layers, and lava tubes. Vesicles are too poorly interconnected to contribute importantly to the permeability. Alteration and secondary mineralization like that described in the caldera-filling rocks is essentially absent in the dissected rift zones, extending at the most only a few hundred feet beyond the caldera boundary.

Information on the geology and hydrology pertinent to the possible occurrence and entrapment of geothermal resources is given in the following sections for each of the areas thought to be most promising for geothermal exploration.

#### East Rift Zone of Kilauea

The east rift zone extends southeastward from Kilauea Caldera for about six kilometers, then bends abruptly east-northeastward and extends through Cape Kumukahi, the eastern point of the island. Beyond the cape it forms a broad east-northeast-trending ridge on the ocean floor for another 65 kilometers (Malahoff and McCoy, 1967). Northwest of the bend the rift zone is marked by a row of pit craters (the Chain of Craters), and a few spatter-and-cinder cones. East-northeast of the bend more than 60 spatter and cinder cones mark the sites of pre-historic, but geologically recent, eruptions along the rift zone. Just before the beginning of written history eruptions took place on the eastern part of the rift zone in about 1750 and 1790. Historic eruptions along it have occurred in 1840, 1922, 1923, 1955, 1960, 1961, 1962, 1963, 1965, 1968, and 1969 to the present.

The area known as East Puna consists of the part of Kilauea Volcano east of about 155° west latitude. It is a broad gently sloping ridge built by lava flows from the east rift zone, and the rift zone extends along its crest. It is situated more or less mid-way between Kilauea caldera and the termination of the rift-zone ridge at the ocean floor. Within it, between the 500-meter contour and sea level, eruptions have occurred in about 1750 and 1790, and in 1840, 1955, and 1960. In 1924, very numerous earthquakes and volcanic tremor accompanied the disappearance of the lava lake

in Kilauea caldera and the sinking of the floor of a graben along the rift zone close to sea level in East Puna; although no molten lava appeared at the surface above sea level it is virtually certain that a large volume of magma moved eastward through the rift zone. The surface expression of the rift zone is about three kilometers wide.

East of Cape Kumukahi the submarine cones along the rift zone appear very fresh in photographs. A submarine eruption occurred a few kilometers offshore in 1884.

Lava flows from vents along the rift zone have poured down slope, building a broad structural arch that plunges east-northeastward at an angle of 1 to 2°. North of the rift zone the lava beds dip 2 or 3° north-eastward. South of it the dips are 2 to 4° southeastward. Locally on the south side of the ridge, dips of more than 6° probably are the result of lava flows mantling a southeast-facing fault scarp (Stearns and Macdonald, 1946, plate 1). The lava flows are of both pahoehoe and aa types. No specific determinations of permeability are available, but similar lavas yield water freely to wells, and over-all permeability is unquestionably high. Large amounts of ground water move through the area, producing many brackish basal springs along the shoreline.

Beneath sea level divers have observed what appear to be pillow lavas, and similar lavas are shown in deeper water by photographs (Moore and Fiske, 1969).

Warm (33° C) brackish water issues in the beach at Pohoiki, 7.6 km south-southwest of Cape Kumukahi. Previous to 1960 warm (29° C) brackish basal water was present in a crack on the rift zone 2.4 km west of the cape, and similar water at 32° C was present in another crack 1 km to the northwest. The cracks lay close to the borders of the graben that sank in 1924. Both

were buried by lava in 1960. A well 6 km west of Cape Kumukahi contained brackish water at  $34^{\circ}$  C. A well 4 km S80<sup>0</sup>W of Pohoiki contains brackish water at  $53^{\circ}$  C. Many steaming vents are present along the rift zone west of 300 meters altitude, but east of that altitude only minor wisps of steam issue, especially in Pawai Crater, a small pit crater 10 km southwest of Cape Kumukahi. At Pahoa, and 8 km to the south along the Pahoa-Kalapana road, wells produce cold basal water of good quality.

The warm-water wells are distinctly more saline than would be expected (Macdonald, 1973) on the basis of normal Hawaiian basal ground water conditions in other areas of similarly high rainfall and rocks of approximately the same permeability. The well nearly west of Pohoiki had, on completion, a chloride content of 6,500 mg per liter (approximately 6,000 p.p.m.), and the well 6 km west of Cape Kumukahi had a chloride content of 320 p.p.m. Thus there are distinct anomalies in ground water conditions in East Puna, and the most probable cause in heating of the sea water saturating the underlying rocks, probably by hot intrusive masses along the rift zone, decreasing the density of the water to the point where it can no longer support the normal Ghyben-Herzberg lens of fresh water.

Although all of the exposed rocks are moderately to highly permeable, it is possible that less permeable material may exist at depth. Along part of the contact where Kilauea overlaps the slope of Mauna Loa, 35 km west of Cape Kumukahi, Kilauea lavas overlap several feet of relatively impermeable weathered volcanic ash (Stearns and Macdonald, 1946, plate 1). This ash layer lies on the crest of a very broad constructional arch built along an ancient east-trending rift zone of Mauna Loa. Magnetic measurements (Malahoff and Woollard, 1966) suggest that this old rift zone of Mauna Loa continues eastward beneath the cover of Kilauea lavas and merges with the east rift zone

of Kilauea approximately at Cape Kumukahi. If so, the ash layer may continue beneath Kilauea lavas to or beyond Cape Kumukahi at some depth below sea level. If it is present, it might conceivably form a tight cap over permeable lavas beneath in such a structural arrangement as to trap or concentrate steam or hot water.

Another possibility for the formation of a zone of less permeable material is related to the presumed history of the submarine growth of the volcano. It is believed that in deep water the eruptions were non-explosive, because of the restraining hydrostatic pressure of the overlying water; but as the volcano grew into shallow water the explosive liberation of magmatic gas became possible, and contact of the erupting magma with water probably caused numerous moderately violent steam explosions like those during the recent eruptions of Surtsey Volcano in Iceland and Capelinhos in the Azores. These would form large amounts of glassy ash that would rapidly become palagonitized. If the ash stayed in place it may constitute an extensive, poorly permeable layer or layers intercalated in the lava flows, possibly forming a relatively tight caprock. Still another possibility is that hyaloclastite, formed in association with pillow lavas and altered to palagonite, may form relatively tight layers in the lava sequence.

Sinking of the island may have carried any of these impermeable layers to considerable depths below the level at which they formed. Thus there is a possibility of stratigraphic and structural traps for several hundreds of meters below sea level.

### Southwest Rift Zone of Kilauea

The second principal rift zone of Kilauea Volcano extends from the caldera southwestward to the coast, and beyond. Little is known about it below sea level. Above sea level it is dotted with about 30 spatter and cinder cones at the vents of prehistoric eruptions. During historic time eruptions occurred along it in 1823, 1868, 1919-1920, and 1971. Vents of the latter eruption, along the upper (northeast) part of the rift zone, are still steaming.

The rift zone is as much as 4 km wide, and near the caldera is bordered by inward-facing fault scarps. Farther southwest the graben structure is less clear, though locally the rift zone is bordered on the northwest by southeast-facing fault scarps. The rift zone lies parallel to, and about 2 to 5 km southeast of, the Kaoiki fault zone, along which the lower slope of Mauna Loa has moved relatively downward in relation to the upper part of the mountain.

The constructional ridge along the southwest rift zone is asymmetrical. Northwestward the Kilauea lavas abut against the slope of Mauna Loa, usually within 2 km of the rift zone. Dips between the rift zone and the Mauna Loa contact are generally about 2 to 3° southwestward, nearly parallel to the rift zone. Southeast of the rift zone dips range from 4 to 6° southeastward. The lava flows are pahoehoe and aa, similar to those of East Puna. The rift zone is marked by innumerable open cracks. One of these, the Great Crack, is uninterrupted for almost 25 km along the lower part of the rift zone, and served as the near-surface conduit for the 1823 lava flow.

Warm water has long been known in a crack in Waiwelawela ("Hot Water") Point, at the coast 4 km southeast of the Great Crack. It is brackish, but neither its salinity nor its temperature have been measured. Anomalous

ground water conditions exist in the area west of the Great Crack, around Pahala and between there and the ocean. Fresh ground water, apparently part of the basal zone of saturation, stands about 70 meters above sea level in the Pahala well. Whether this high level of ground water is in any way related to the southwest rift zone of Kilauea is unknown. It could result from obstruction of seaward movement of the ground water by faults of the Kaoiki system and/or numerous relatively impermeable dikes in the rift zone, possibly combined with unexposed poorly permeable tephra and/or hyaloclastite below present sea level. The Pahala ash, which is largely palagonitized, reaches thicknesses of as much as 17 meters near Pahala, and is presumably down-dropped along the Kaoiki fault system and buried by later lavas farther seaward.

#### Southwest Rift Zone of Mauna Loa

One of the two principal rift zones of Mauna Loa extends southwestward from the summit caldera to an altitude of about 2,300 meters, then broadens and turns southward to Ka Lae (South Point). Above 2,300 meters altitude the rift zone is approximately 3 km wide, and is studded with many spatter-and-cinder cones, spatter ramparts, and open fissures. Just south of the caldera are three pit craters. Below 2,300 meters the rift zone broadens to about 6 km, but at about 1,100 meters the western part of the zone dies out and the eastern part continues southward. This southward extension is only about 2 km wide. Along its western edge, the north-trending Kahuku fault has formed a westward-facing scarp 180 meters high near the coast, gradually decreasing in height inland and disappearing near the highway at 600 meters altitude. Between 760 and 975 meters altitude, the Pali o ka Eo is probably a buried west-facing scarp en echelon with, and slightly east



of, the Kahuku fault. The rift-zone ridge and the Kahuku fault scarp can be traced southward on the ocean floor for about 35 km behind South Point.

A pit crater lies near the eastern edge of the rift zone at 1,370 m altitude, and three other small ones lie close to the top of the Kahuku fault scarp between 530 and 565 m altitude. These pit craters are partly buried by Pahala Ash, showing that the rift zone has been active at least since the latter part of the eruption of the Kahuku Volcanic Series (Stearns and Macdonald, 1946).

Most of the lavas along the southwest rift zone of Mauna Loa belong to the Kau Volcanic Series (Stearns and Macdonald, 1946). They are tholeiitic basalts of both pahoehoe and aa type, similar to those of Kilauea. East of the rift zone and along the top of the Kahuku fault scarp the Kau lavas rest on Pahala Ash, which in this region ranges from about 2 to 8 m in thickness. The ash is largely palagonitized. Beneath the ash, in Kahuku scarp 180 m of thin-bedded tholeiitic pahoehoe and aa lava flows of the Kahuku Volcanic Series are exposed. No ash beds are intercalated with the lavas below the Pahala Ash.

Since 1832, seven eruptions have taken place along the southwest rift zone. Most were from vents above 2,300 meters altitude, but in 1868 an eruption took place from fissures near the eastern edge of the rift zone between 600 and 1,100 meters altitude. Lava from the fissures flowed into the ocean west of the Kahuku fault scarp, the more easterly of the two major flows lying directly against the base of the scarp. One of the two largest eruptions of Mauna Loa in history took place in 1950, pouring out more than 460,000,000 cubic meters of lava from vents between 2,400 and 3,800 meters altitude on the southwest rift zone (Finch and Macdonald, 1953).

No historic movement is known to have occurred on the Kahuku fault. During a strong (intensity X mm) earthquake in 1868, movement occurred on the Waiohinu fault, 8 km east of the Kahuku fault. It is inferred that other movement occurred at the same time beneath the ocean, because a big local tsunami was generated, but no movement was observed on the Kahuku fault above sea level.

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The geophysical background is reviewed in Section II of the geophysics program in this proposal.

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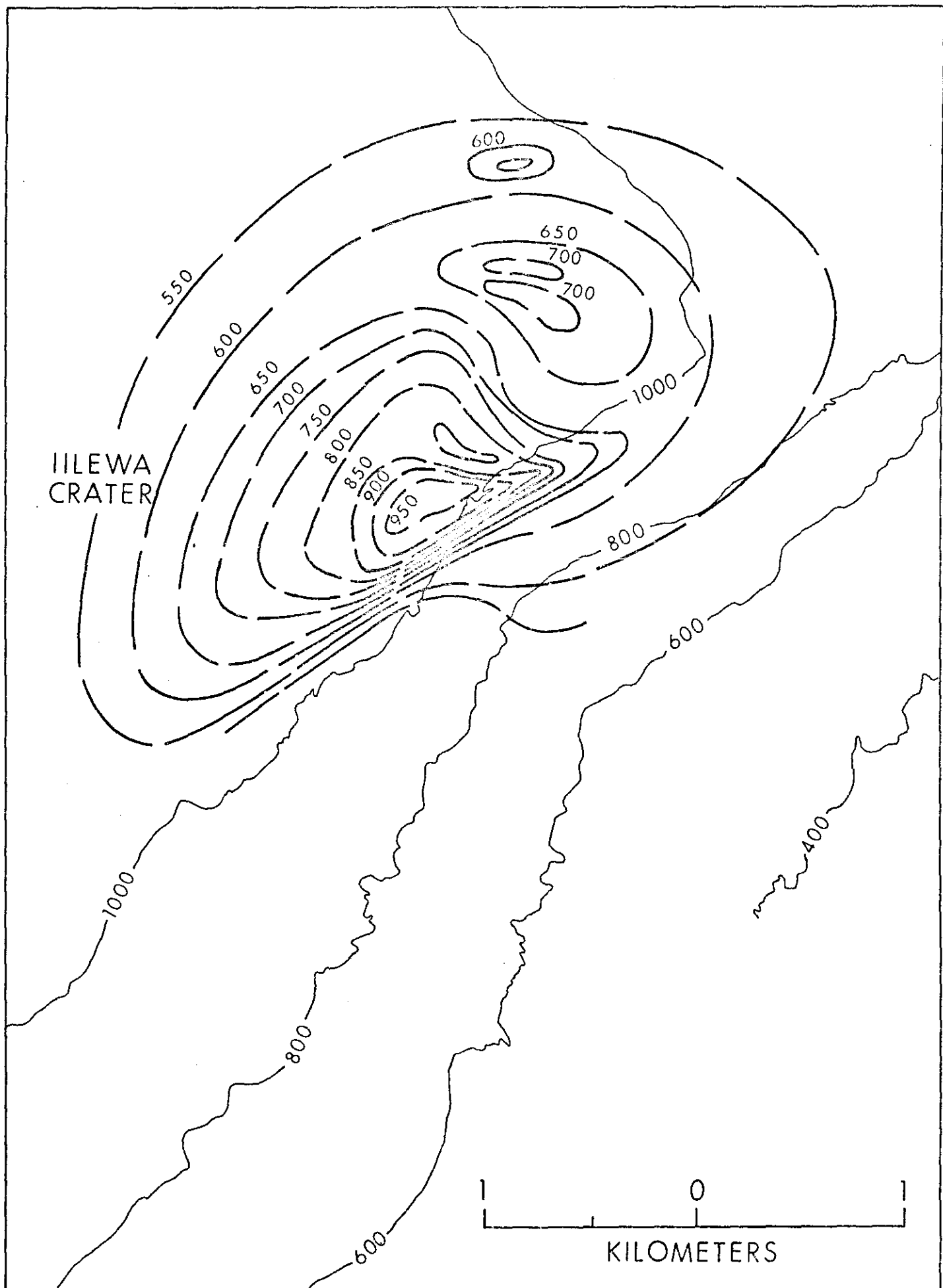
## SELF POTENTIAL STUDY

Charles J. Zablocki

Studies made by the U.S. Geological Survey in many areas of Kilauea in recent years have indicated that self potential measurements appear to be the single most useful method for identifying anomalous thermal areas. Anomalies have also been found in areas which have no obvious surface manifestations. Their locations, however, are in areas which reasonably could contain localized heat sources.

In brief, the large potentials observed at the surface are thought to be related to the flow of hydrothermal fluids in a convection system (electrofiltration phenomenon). Although most of these studies have been made near and at the summit of Kilauea, some measurements made in a few areas of the lower east rift zone (Puna district) have revealed some interesting findings (Figure 1). Not only were large potentials observed over the still-steaming vents of the 1955 eruption ( 3 miles south of Pahoa ), but the asymmetry of the resulting contoured data suggest a north dip to the related intrusion (Figure 2). Measurements made about 4 1/2 miles farther east along the rift zone delineated an anomaly in an area that has no surface indications of near-surface heat source (Figure 3). Only weak anomalies were observed over some of the 1955 eruptive fissures nearby. Curiously, the large anomaly is located in the area where the 1955 rift eruption was offset and coincides with the general epicentral area of recurrent shallow earthquake swarms in recent years.

Because of these results, a cooperative study is presently underway with the U.S. Geological Survey to make a detailed survey of the lower east rift zone of Kilauea in an effort to help locate the sites for the exploratory drilling program.



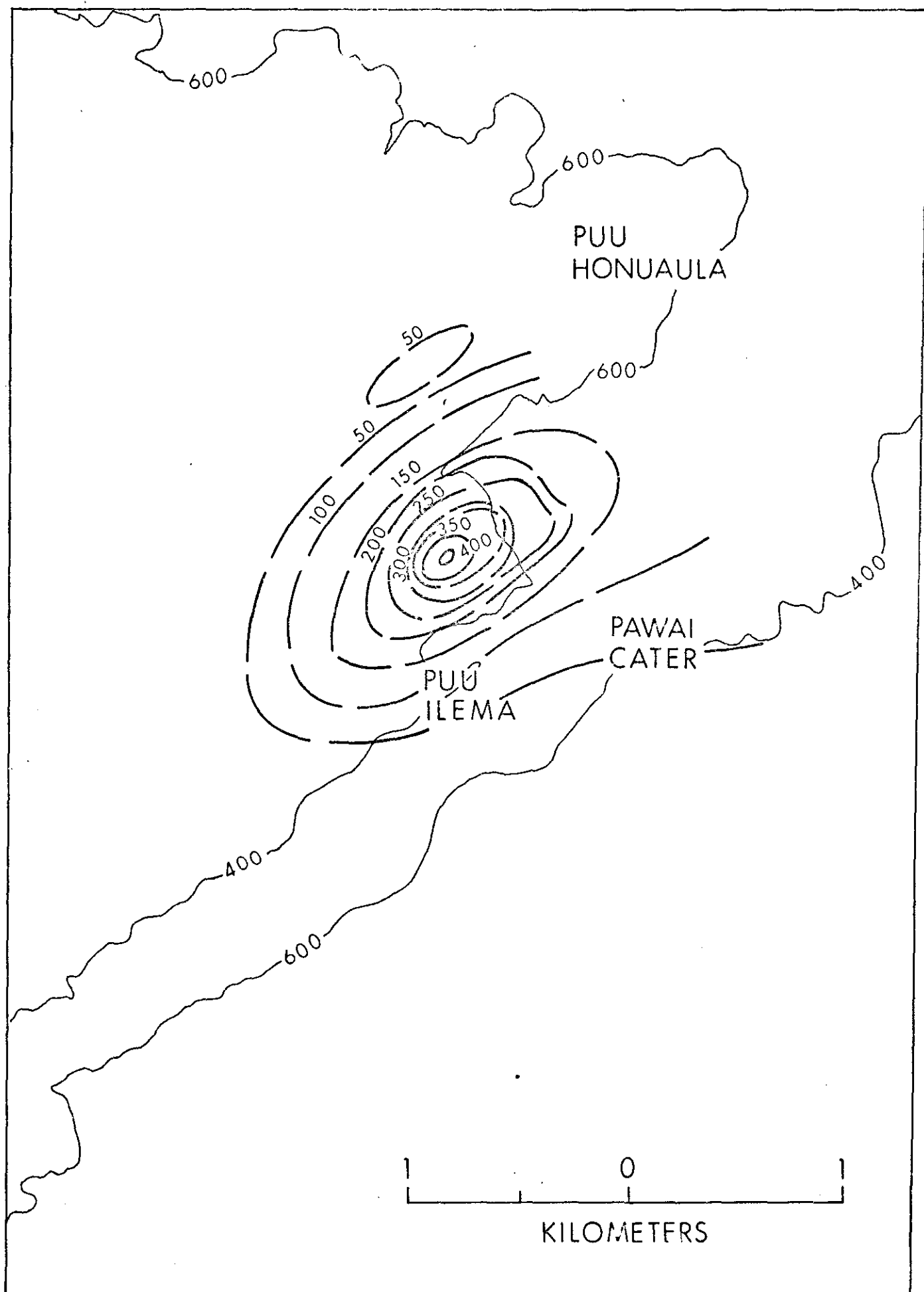


Figure 3

Self Potential Countours

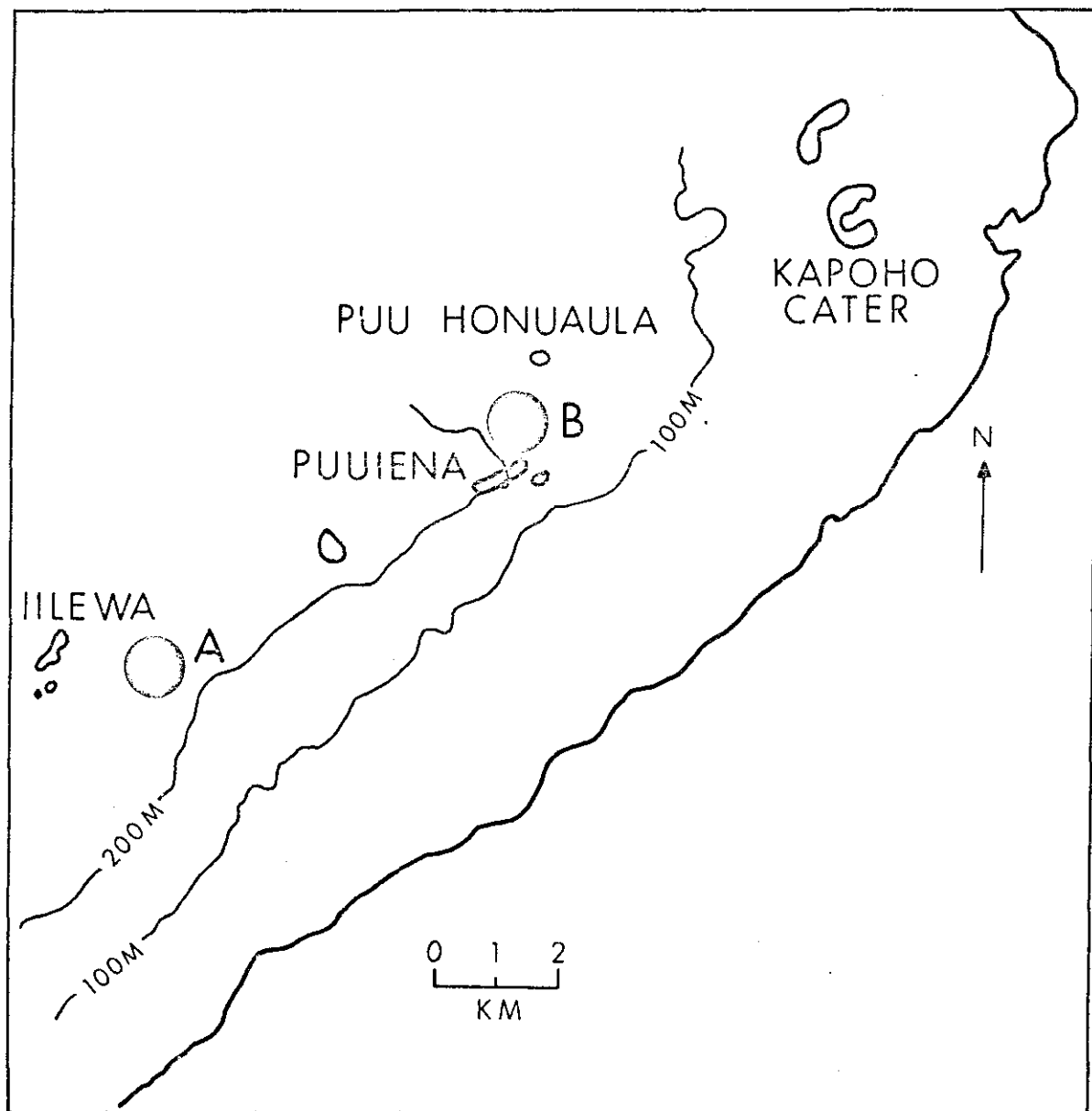


Figure 1  
Areas Measured

Imagery from Infrared Scanning of the East  
and Southwest Rift Zones of Kilauea and the Lower Portion  
of the Southwest Rift Zone of Mauna Loa, Island of Hawaii

Agatin T. Abbott

## INTRODUCTION

From July 31 through August 4, 1973 night time flights for obtaining infrared imagery along the east and southwest rift zones of Kilauea and the southwest rift zone of Mauna Loa were undertaken on the island of Hawaii. Flights were also made on Hualalai and Kohala volcanoes but because of inconclusive results are not included in this report. Ground control stations had been established during daylight hours several days prior to starting the flight program. Students stationed at the ground central points guided the aircraft on predetermined flight paths by the use of directional lights which were visible to the plane's navigator. Results of the infrared scanning program are considered to be very successful. Events leading up to the final imagery on 8 x 10 color prints will be discussed below.

The sum of \$23,900 was designated by the NSF to be expended on aerial photo-geologic work on the Hawaii Geothermal Project. Infrared scanning was the only aerial technique employed in this phase.

A firm specializing in infrared surveys, Dadaelus Enterprises of Ann Arbor, Michigan was selected as best equipped and experienced in Hawaiian conditions to accomplish the infrared imagery survey. Towill Engineering Corporation of Honolulu provided the aircraft, pilot and navigator and submitted a report with maps and black and white aerial photographic mosaics. These firms earlier the same year had flown paths for Dr. George Keller of the Colorado School of Mines, who was engaged in locating a deep drill hole near the summit of Kilauea.



## FLIGHT PATHS AND DESCRIPTIONS

### 1. East Rift Zone of Kilauea

Two long parallel flight paths were flown along the East rift zone from points outside the boundary of Hawaii Volcanoes National Park to Cape Kumakahi. Shorter paths crossing the two long parallel lines were flown at the intersection of the rift zone with the main highway between Pahoa and Kalapana. Approximately 35 line miles of usable records was obtained. From this the following strips were selected for reproduction in infrared false color imagery.

Three miles of flight paths high on the rift zone at an average ground elevation of 2100 feet provide excellent examples of rift lineation and temperature aureoles. The DIGICOLOR prints showed a temperature range of  $14^{\circ}\text{C}$  to  $20^{\circ}\text{C}$ . Numerous sites along the rift showed spots of white color indicating the temperature exceeded the highest range on that temperature set. This is not surprising in view of the fact that wisps of steam are issuing from some of the vents probably as a result of meteoric water coming in contact with residual heat of lavas from the 1966 eruptions in this area. Downslope from the steam vents, a fairly extensive area shows a slightly higher surface temperature than its surroundings, by an average of  $1^{\circ}\text{C}$ .

The area for the second set of DIGICOLOR prints in the Kilauea east rift zone was selected from a flight path of approximately two miles in length across the area of intersection of the rift zone and the Pahoa-Kalapana highway at a ground elevation of approximately 1000 feet. The temperature range of this path is  $16^{\circ}\text{C}$ - $25^{\circ}\text{C}$  or  $1.5^{\circ}\text{C}$  per color. Again numerous sites showing white along the rift zone indicate hot spots and an aureole of decreasing temperatures are distributed outward from the rift. Fine examples of surface temperature zones are demonstrated in this imagery.

## 2. Southwest Rift Zone of Kilauea

A flight path 12 miles long was followed from the point of intersection of the western boundary of Hawaiian Volcanoes National Park and the main highway between Kilauea summit to Pahala to a point on the sea coast approximately 4 miles east of Punaluu.

The altitude maintained was about 3000 feet above ground level. Throughout most of the strip a thermal anomaly was evident along the Great Crack. The temperature range on the flight path was 18°C-22°C. Of unusual interest on this path is a thermal anomaly in a target-like pattern near the southern end of the Great Crack approximately 1 ¼ mile from the coastline at an elevation of 300 feet above sea level. The target-like pattern is 1200 feet wide 1600 feet long. The roughly circular pattern of thermal anomaly lies 600 feet northwest of a splinter extension of the Great Crack. The highest temperature within the target area reaches the red color of 22°C in two small spots, and within the Great Crack extension, small local spots reach white, or off scale.

The anomaly appears to be associated with the lower slopes along the south side of Puu Kolekole, a prehistoric cinder cone, and with the extension of the Great Crack.

This surface thermal anomaly as registered by infrared scanning imagery should receive careful attention as a potential area for further geophysical investigation and possible research drilling.

## 3. The Southwest Rift Zone of Mauna Loa

A flight path with the total length of approximately 22 miles followed the southwest rift of Mauna Loa from an elevation of approximately 7000 feet above sea level to the tip of South Point. Only the lowest five mile section of this path to the tip of South Point showed any significant thermal anomalies. This portion has been reproduced in DIGICOLOR and prints developed.

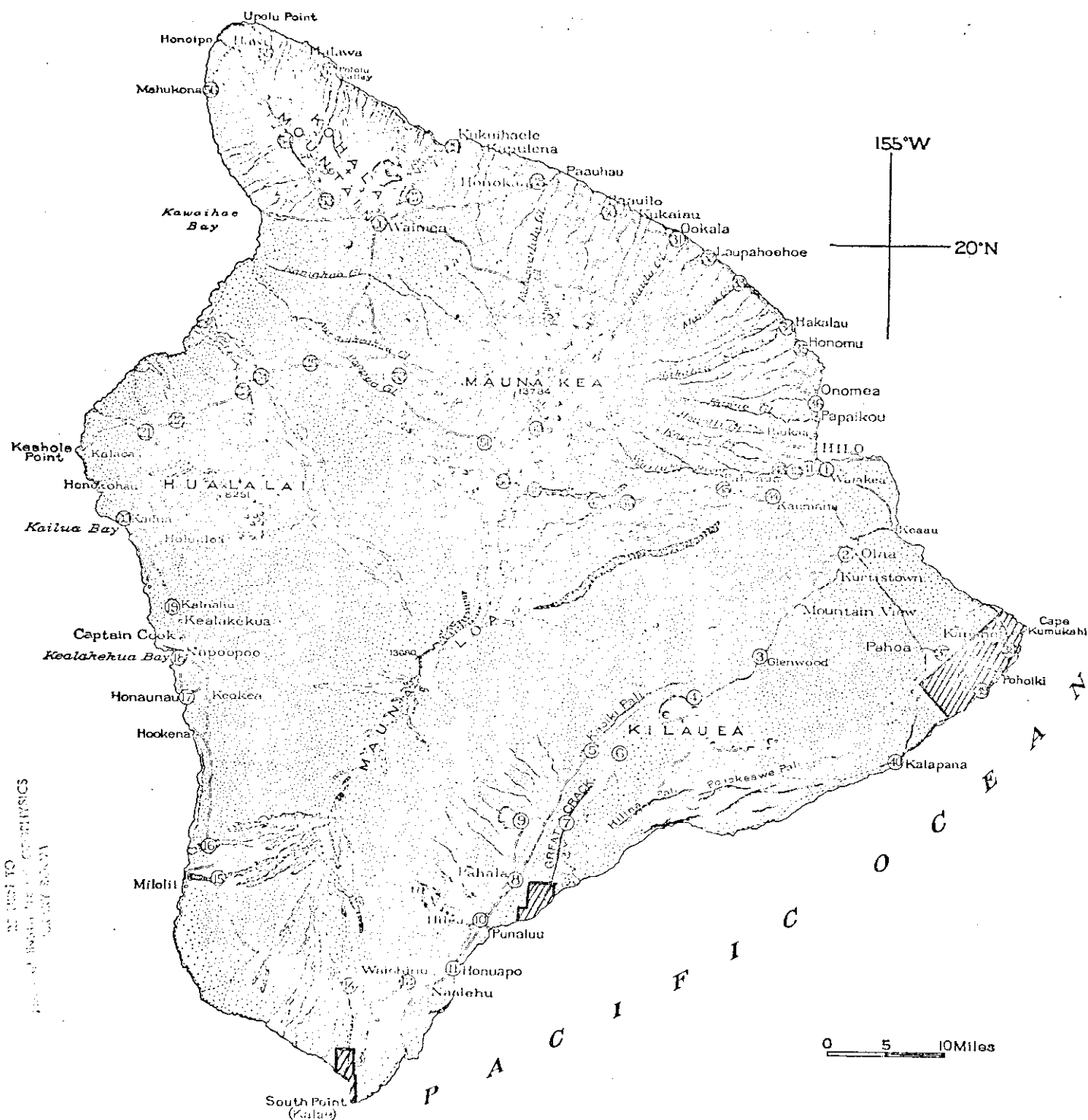
The temperature range on one sub-set is  $16^{\circ}\text{C}$ - $22^{\circ}\text{C}$ . Thermal anomalies appear along the cliff face of the Kahuku fault as clusters along the base of the cliff and as linear features possibly indicating bedding planes in the lava flows. Numerous spots along the cliff register red and a few local areas show white, or off scale.

The cause of these anomalies is not known at the present time. The Kahuku fault scarp, which reaches 400 feet in height in this area, faces west. Consideration must be given to the possibility that the anomalies result from residual late afternoon solar heat. The imagery was taken at 0030 hours in order to reduce the effect of residual heat. The physical distribution of the warmer areas does not appear to show a pattern that might be caused by residual heating, none the less this factor must be kept in mind.

Another, more intriguing possibility lies in the concept that heat may be rising from depth along the plane of the Kahuku fault and issuing at the base of the cliff and along bedding planes of the lava flows. The Kahuku fault is a major structural feature of Mauna Loa shield volcano. It extends ten miles inland from the coast and has been followed out to sea for a distance of over 15 miles. Depth recordings made on board the R/V Valdivia in 1973 while steaming past the extension of the fault 4 miles off shore registered a vertical displacement along the fault plane of 1900 meters.

Further geophysical and geological work should be concentrated in the section of the lower portions of the Kahuku fault. This may have promise as an area in which to locate an array of research drill holes.

Also of interest along the South Point shoreline as registered by the infrared imagery is the temperature distribution in the sea water. Directly offshore a large patch of water shows as a white area indicating that its temperature is greater than  $22^{\circ}\text{C}$ . It is not recognized at this time whether this is a bay of warm surface water brought in by ocean currents or wind or whether the warming is caused by some other process.



Index Map Showing Three Principal Areas Under Consideration for Exploratory Research Drilling on the Island of Hawaii. (Map after Stearns and Macdonald, Bull. 9, Hawaii Division of Hydrography)

## CURRENT RESEARCH SUPPORT FOR PRINCIPAL INVESTIGATOR

The following is a listing of the extramurally-funded projects for Agatin T. Abbott, Principal Investigator of the Drilling Program.

1. Survey of Natural Areas of Pacific Island Territories  
U.S. Department of the Interior, National Park Service
2. Survey in the Hawaiian Islands  
U.S. Department of the Interior, National Park Service

VITAE AND BIBLIOGRAPHIES FOR  
DRILLING PROGRAM

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Professor of Geology

EDUCATION: B.A., University of Minnesota, 1943  
Ph.D., University of Washington, 1953

PAST EMPLOYMENT:

1939-1944	Mining Geologist in Southwest United States, employed by American Smelting and Refining, Phelps Dodge Corporation, and Illinois Zinc Company
1944-1946	Lieutenant (j.g.), USNR
1946-1947	Project Engineer, Arizona Highway Department
1947-1949	Consulting Geologist, Prescott, Arizona
1949-1952	Teaching Fellow and Instructor, University of Washington
1952-1955	Assistant Professor of Geology, School of Mines; Geologist, Idaho Bureau of Mines and Geology; Consultant, Bear Creek Mining Company
1955-1964	Professor and Chairman of Geology, University of Hawaii
1955-1972	Consultant: Reynolds Metals Company; Walter Lum & Associates; Parsons-Brinkerhoff, Inc.; Hawaii Thermal Power Company; U.S. Navy - Operation Sailor Hat  In Addition: Director, National Science Foundation Institute for Science Teachers, Palau Islands, 1969  Instructor, National Science Foundation Institute for Science Teachers, Japan, 1966-67  Director, National Science Foundation for Science Teachers Television Series, Hawaii, 1967  Member, State of Hawaii Panel for Development of Geothermal Resources, 1970-72
1973-Present	Professor and Chairman of Geology and Geophysics, University of Hawaii

CURRENT RESEARCH

Involves the investigation of thermal areas in Hawaii for possible sources of geothermal energy.

Also, research of manganese nodules and crust in the Hawaii area; visiting scientist on West German ship R/V VALDIVIA, on cruise May 29 to June 26, 1973.

PRINCIPAL PUBLICATIONS

- International Symposium on the Origin and Distribution of Manganese Nodules in the Pacific and Prospects of Exploration, July 1973. (Paper presented: International Cooperation Between the R/V VALDIVIA and the Hawaii Inst. of Geophysics.)
- U.S.-Japan Cooperative Science Seminar on Utilization of Volcano Energy, Hilo, Hawaii, Feb. 1974. "Imagery from Infrared Scanning, Island of Hawaii."
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University of Hawaii Press, 1973.

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EDUCATION:      Ph.D., University of California, 1938

PAST EMPLOYMENT:

1938-1939	Assistant Geologist, Shell Oil Company
1939-1947	Assistant Geologist and Associate Geologist, U. S. Geological Survey
1946-1947	District Geologist for the Hawaiian Islands
1947-1948	Assistant Professor of Geology, University of Southern California
1948-1958	Geologist, U. S. Geological Survey
1951-1956	Director of Hawaiian Volcano Observatory
1958-Present	Senior Professor of Geology, University of Hawaii

OTHER ACTIVITIES:

Former President, Section of Volcanology and  
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Former President, International Association  
of Volcanology and Chemistry of the Earth's  
Interior

PRINCIPAL PUBLICATIONS:

Of about 150 published papers in general geology, petrology,  
geophysics, and volcanology, those most pertinent to the present proposed work  
are listed as follows:

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Ph.D., Stanford University, 1961

PAST EMPLOYMENT:

1952-1963	Field projects, in Arizona, Mineral Deposits Branch, U. S. Geological Survey
1963-1965	Chief, Technical Reports Unit, Menlo Park, U. S. Geological Survey
1965-1968	Field projects in Arizona, California, Hawaii, U. S. Geological Survey
1968-1970	Staff Geologist, Office of Mineral Resources, Washington, D. C.
1970-Present	Scientist-in-Charge, Hawaiian Volcano Observatory, U. S. Geological Survey

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PAST EMPLOYMENT:

1954 Physicist engaged in semiconductor research, IBM Corporation

1955-Present U. S. Geological Survey  
Background includes electrical and magnetic properties measurements of ore deposits, design and application of various electrical and electro-magnetic techniques, extensive applications of borehole logging methods in mining exploration drill holes, and analysis of EM transients associated with nuclear explosions. At present, applying electrical and magnetic methods to the study of Kilauea Volcano, Hawaiian Volcano Observatory.

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## HAWAII GEOTHERMAL PROJECT

### PHASE II

#### RELATED PROGRAMS AND ACTIVITIES

##### A. Related Programs At The University of Hawaii

Currently there is a great deal of research interest at the University of Hawaii on projects which have direct relevance to the HGP. The Hawaii Institute of Geophysics has competence in geophysical exploration, a good knowledge of the geophysical features of the Big Island and the State of Hawaii in general, and experience with test drillings. The Water Resources Research Center has been conducting research on the ground water hydrology of the Islands and is familiar with the rainfall, water distribution, and flow patterns of the islands.

The Environmental Center at the University is concerned with the preservation and protection of the environment in Hawaii. Its cooperation and input complement the efforts of the HGP. The Sea Grant Program of the University also has energy-related interests, while the College of Engineering has staff competence and interest in power systems, direct energy conversion, and transmission of electrical energy.

A new program enacted by the 1974 State Legislature establishes a Natural Energy Institute at the University (copy of House Bill 2376-74 attached). The purpose of this Institute is to provide focus, direction, and support for research on natural energy systems -- including geothermal resources.

##### B. Related Programs In Other Organizations

A research program of considerable interest to the HGP has been the investigation of the hydrothermal systems at Kilauea Volcano on the Island of Hawaii by Dr. G. V. Keller of the Colorado School of Mines. The program, which has also been funded by NSF, has used Kilauea Volcano to study the

*Amended to SB 1645*

H. B. NO. 2376-7

A BILL FOR AN ACT

ESTABLISHING THE HAWAII NATURAL ENERGY INSTITUTE AND MAKING AN  
APPROPRIATION FOR PLANNING THE STRUCTURE AND OPERATION  
THEREOF.

BE IT ENACTED BY THE LEGISLATURE OF THE STATE OF HAWAII:

1       SECTION 1. The current energy crisis is caused by a  
2 global energy shortage which will worsen through the remainder  
3 of this decade and may continue to the end of this century.  
4 The State of Hawaii, with its total dependence for energy on  
5 imported fossil fuel, is particularly vulnerable to dislocations  
6 in the global energy market. This is an anomalous situation,  
7 as there are few places in the world so generously endowed  
8 with natural energy: geothermal, solar radiation, ocean  
9 temperature differential, wind, waves, and currents--all  
10 potential non-polluting power sources. The purpose of this  
11 Act is to establish the Hawaii Natural Energy Institute that  
12 will coordinate and undertake the development of non-polluting  
13 natural energy sources for Hawaii; and, to make an  
14 appropriation for planning the structure and subsequent  
15 operation of the Institute. Although the ultimate structure  
16 of the Institute will not be determined until after a year  
17  
18

1 of planning and development, its immediate establishment as  
2 provided herein will provide the needed visibility, focus  
3 and encouragement for energy related activities directed  
4 toward converting Hawaii's natural resources into viable  
5 energy systems. These alternative energy systems will:

- 6 (1) Diminish Hawaii's total dependence on imported  
7 fossil fuels,
- 8 (2) Meet the State's increasing energy demands with  
9 little or no environmental degradation, and
- 10 (3) Contribute to the technology base for finding  
11 solutions to the national and global energy  
12 shortage.

13 SECTION 2. The Hawaii Natural Energy Institute is  
14 hereby established as a research unit at the University of  
15 Hawaii-Manoa. The President of the University of Hawaii  
16 will appoint from appropriate University staff an Energy  
17 Planning Committee and designate its chairman. This  
18 Committee will serve as a steering committee and the Chairman  
19 shall be the Acting Director of the Institute during the initial  
20 year both for carrying out the operations and functions  
21 of the Institute and for planning the ultimate organizational  
22 structure. Nationally recognized energy planners may be  
23 consulted on specific goals and general organizational  
24  
25

1 structure of the Energy Institute. The President will also  
2 appoint a broadly based Policy Advisory Committee to provide  
3 interaction between interested segments of the community  
4 and the Energy Planning Committee. A report containing  
5 recommendations for the structure and subsequent operation  
6 of the Energy Institute will be prepared by the Energy  
7 Planning Committee for presentation to the Legislature  
8 twenty (20) days before the beginning of the 1975 Session.

9 SECTION 3. There is appropriated out of the general  
10 revenues of the State the sum of fifty-five thousand dollars,  
11 or so much thereof as may be necessary, to be expended by the  
12 University of Hawaii for planning the structure and subsequent  
13 operation of the Hawaii Natural Energy Institute, and for  
14 the hiring of necessary staff and consultants during the  
15 next fiscal year.

16 SECTION 4. This Act shall take effect July 1, 1974.  
17

18 INTRODUCED BY:

*Lance Besser*  
*by request*

FEB 6 1974

hydrothermal aspects of a geothermal system. Dr. Keller's geophysical studies of the summit area and the results of the 4137-foot drill hole have provided important scientific information to the HGP in interpretation of geophysical data and in planning for the drilling program.

Another project with which the HGP has established close interaction is the Stanford Geothermal Project, also funded by NSF, with Drs. Paul Kruger and Henry Ramey as Co-P.I.'s. Dr. Ramey has been an active consultant to the Engineering Program from the initial phase of the HGP and continues to provide assistance and communication with geothermal-related programs on the Mainland. This includes the Geysers and Imperial Valley, which have been visited extensively by our staff.

Members of the National Liaison Board, discussed in the Management Program, provide an exchange of information with the Marysville Project; Republic Geothermal, Inc; Battelle Northwest; Rogers Engineering; the Geothermal Officer for the State of California; and the U.S. Geological Survey. Good communication has also been established with AEC Laboratories at Los Alamos, Berkeley, and Livermore, as well as with the Sandia Corporation at Albuquerque.

Some exchange has taken place with scientists and engineers involved with geothermal projects in Italy, New Zealand, and Japan. Because of Hawaii's geographic location as the hub of the Pacific, HGP staff have frequent opportunity to discuss geothermal projects with scientists enroute to destinations both East and West.

The concept of a National Geothermal Energy Laboratory for Hawaii will permit researchers from other states and countries to utilize the Laboratory to further their own investigations. This will facilitate the dissemination of research results and the interaction of researchers from different organizations working on similar projects.

### C. Dissemination Of Research Results

As discussed in the previous section, the most effective exchange of information with potential beneficiaries of the research at the local level is through the 16-member Hawaii Advisory Committee, and at the national level with the nine-man Liaison Board.

To date the actual results of the HGP research programs have been rather sparse, but staff have already submitted papers for publication through the normal channels of the scientific and technical press, and will aggressively pursue this vehicle as research results unfold. In addition, geothermal energy is sufficiently timely and novel to have popular appeal, so there has been extensive coverage in the regular news media.

Most of the reports on the HGP to date have been general descriptions of the project and an overview of goals and objectives. Such reports have been presented to a variety of meetings in this country, as well as at the joint U.S.-Italy Geothermal Conference at Pisa in December 1973. A discussion of the infrared scanning program was presented to the U.S.-Japan Conference on Utilization of Volcano Energy, held in Hawaii in February 1974. Dr. Furumoto was co-chairman of this conference.

Locally the project has been brought to the attention of both potential beneficiaries of the research, as well as the general public, through over thirty talks and illustrated lectures to professional organizations, civic, and citizen groups. The Center for Engineering Research at the University sponsors a series of seminars, with assistance from NSF, on Environmental Conferences on the Public Understanding of Science for Hawaii. This ECOPUSH Series included a major conference on "Future Technologies for Hawaii", which provided an excellent forum for presenting a progress report on the development of geothermal energy in Hawaii.



#### D. Application To Other Federal Agencies

The proposal has not been submitted to any other Federal agencies for total or partial support. Preliminary discussions have been held, however, with the Atomic Energy Commission on possible funding of later phases of this project in the development of a prototype geothermal power plant.

To the initial State and County of Hawaii funding of \$200,000 for geothermal research, the 1974 Legislature earmarked an additional \$500,000 for exploratory geothermal drilling, contingent upon Federal matching. Although efforts will be made to identify total research drilling support from Federal sources, if these funds are inadequate to complete the drilling program, a request will be made to the Governor to release a portion or all of this \$500,000 for exploratory drilling.

## BUDGET SUMMARIES

Direct support to the Hawaii Geothermal Project through December 31, 1974 is as follows:

National Science Foundation - RANN	\$252,000 (FY 73)
	216,000 (FY 74)
	124,000 (FY 75 committed)
State of Hawaii CIP Budget	100,000 (FY 72)
	500,000 (FY 74 appropriated)
County of Hawaii CIP Budget	100,000 (FY 72)
Sandia Laboratories - AEC	12,000
Hawaiian Electric Company	9,000
Office of Marine Affairs - State of Hawaii	5,000
Private Contributions	13,000
	<hr/>
	\$1,331,000
	<hr/>

In addition to the above funding, the University of Hawaii provides significant support to the Project in faculty and staff salaries, support services, equipment, and facility usage.

For support of Phase II of the Project, \$1,986,513 is requested. Table B-I gives a summary of the funding being requested from the Foundation for Phase II of the Project, broken down by program and task. Following this table are individual NSF Form 569 budget sheets for each task. The task budget sheets are arranged by programs with a total program budget sheet preceeding the individual task budget sheets.

HAWAII GEOTHERMAL PROJECT  
 PHASE II  
 BUDGET SUMMARY BY PROGRAM AND TASK

MANAGEMENT

1.0	Coordination and Support	\$ 39,401
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GEOPHYSICAL PROGRAM

2.0	Coordination and Support	\$ 43,454
2.2	Geoelectric Surveys	58,709
2.3	Modelling, Magnetic & Gravity Surveys	33,625
2.4	Temperature Survey	43,124
2.5	Seismic Studies	57,000
2.6	Geochemical Surveys	36,718
2.7	Hydrology	35,107
2.8	Physical Properties of Rocks	<u>49,191</u>
		356,928

ENGINEERING PROGRAM

3.0	Coordination and Support	41,774
3.1	Geothermal Reservoir Engineering	122,892
3.6	Optional Geothermal Plant Design	<u>87,781</u>
		252,447

ENVIRONMENTAL-SOCIOECONOMIC PROGRAM

4.0	Coordination and Support	24,824
4.1	Environmental Aspects	42,313
4.2	Legal and Regulatory Aspects	6,800
4.3	Land-Use and Planning Aspects	11,415
4.4	Economics	<u>46,411</u>
		131,763

EXPLORATORY RESEARCH DRILLING PROGRAM

5.0	Coordination and Support	1,205,974
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	<hr style="border: 0; border-top: 1px solid black; margin-bottom: 5px;"/> TOTAL PHASE II BUDGET <div style="text-align: right;">\$1,986,513</div> <hr style="border: 0; border-top: 3px double black; margin-top: 5px;"/>
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TABLE B-I

# Management

## Task 1.0

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		RESEARCH GRANT BUDGET WORKSHEET	
II. INSTITUTION AND ADDRESS  University of Hawaii Honolulu, Hawaii 96822		NSF PROGRAM  HAWAII GEOTHERMAL PROJECT	PRINCIPAL INVESTIGATOR(S)  John W. Shupe
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT
			\$
A. SALARIES AND WAGES		NSF Funded Man Months (to the nearest tenth)	
1. Senior Personnel		Cal.	Acad.
a. <input type="checkbox"/> (Co) Principal Investigator(s)			1.0
b. <input type="checkbox"/> Faculty Associates			
Sub-Total			
2. Other Personnel (Non-Faculty)			
a. <input type="checkbox"/> Research Associates—Postdoctoral			
b. <input type="checkbox"/> Non-Faculty Professionals			
c. <input type="checkbox"/> Graduate Students			
d. <input type="checkbox"/> Pre-Baccalaureate Students			2,026
e. <input type="checkbox"/> Secretarial—Clerical			9,938
f. <input type="checkbox"/> Technical, Shop, and Other			
TOTAL SALARIES AND WAGES			15,265
B. STAFF BENEFITS IF CHARGED AS DIRECT COST			2,664
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)			17,929
D. PERMANENT EQUIPMENT			
E. EXPENDABLE EQUIPMENT AND SUPPLIES			850
F. TRAVEL 1. Domestic (Including Canada) (including inter-island travel and 2. Foreign travel for local & nat'l advisory committees)			9,000
G. PUBLICATION COSTS			1,000
H. COMPUTER COSTS IF CHARGED AS DIRECT COST			
I. OTHER DIRECT COSTS Xerox Charges 800 Communications 800 Consultants 2,000			3,600
J. TOTAL DIRECT COSTS (C through I)			32,379
K. INDIRECT COSTS			7,022
L. TOTAL COSTS (J plus K)			39,401
M. AMOUNT OF THIS AWARD (ROUNDED)			\$
REMARKS: Use extra sheet if necessary			
* Includes anticipated 10% salary increase.			

GEOPHYSICAL PROGRAM  
BUDGET SUMMARY

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		RESEARCH GRANT BUDGET WORKSHEET	
INSTITUTION AND ADDRESS  University of Hawaii Honolulu, Hawaii 96822		NSF PROGRAM  HAWAII GEOTHERMAL PROJECT	PRINCIPAL INVESTIGATOR(S)  A. S. Furumoto
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT \$
A. SALARIES AND WAGES		NSF Funded Man Months (to the nearest tenth)	
1. Senior Personnel		Cal. Acad. Summ.	
a. <u>3</u> (Co) Principal Investigator(s)		3.0	
b. <u>4</u> Faculty Associates		11.50 2.0	
Sub-Total		26,065 *	
2. Other Personnel (Non-Faculty)		NSF CRANT BUDGET	
a. <u>2</u> Research Associates—Postdoctoral		25,044	
b. Non-Faculty Professionals			
c. <u>11</u> Graduate Students		60,235	
d. <u>13</u> Pre Baccalaureate Students		14,525	
e. <u>1</u> Secretarial—Clerical		9,960	
f. <u>10</u> Technical, Shop, and Other		18,980	
TOTAL SALARIES AND WAGES		154,809	
B. STAFF BENEFITS IF CHARGED AS DIRECT COST		16,044	
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)		170,853	
D. PERMANENT EQUIPMENT		25,300	
E. EXPENDABLE EQUIPMENT AND SUPPLIES		27,412	
F. TRAVEL 1. Domestic (Including Canada)		27,875	
2. Foreign		2,900	
G. PUBLICATION COSTS		7,300	
H. COMPUTER COSTS IF CHARGED AS DIRECT COST		7,282	
I. OTHER DIRECT COSTS		17,940	
J. TOTAL DIRECT COSTS (C through I)		286,862	
K. INDIRECT COSTS		70,066	
L. TOTAL COSTS (J plus K)		356,928	
M. AMOUNT OF THIS AWARD (ROUNDED)		\$	
REMARKS: Use extra sheet if necessary			
*Includes anticipated 10% salary increase.			

## SUPPORT &amp; COORDINATION

## Task 2.0

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		RESEARCH GRANT BUDGET WORKSHEET	
INSTITUTION AND ADDRESS		NSF PROGRAM	PRINCIPAL INVESTIGATOR(S)
University of Hawaii Honolulu, Hawaii 96822		HAWAII GEOTHERMAL PROJECT	A. S. Furumoto
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT
			\$
A. SALARIES AND WAGES		NSF Funded Man Months (to the nearest tenth)	
1. Senior Personnel		Cal.	Acad.
a. <u>1</u> (Co) Principal Investigator(s)			1
b. _____ Faculty Associates			
Sub-Total		2,186	
2. Other Personnel (Non-Faculty)			
a. _____ Research Associates—Postdoctoral			
b. _____ Non-Faculty Professionals			
c. _____ Graduate Students			
d. <u>1</u> Pre-Baccalaureate Students <u>400 Hrs. @ \$2.75/hr.</u>			1,100
e. <u>1</u> Secretarial—Clerical			9,960
f. <u>1</u> Technical, Shop, and Other			10,800
TOTAL SALARIES AND WAGES		24,046	
B. STAFF BENEFITS IF CHARGED AS DIRECT COST		4,182	
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)		28,228	
D. PERMANENT EQUIPMENT			
E. EXPENDABLE EQUIPMENT AND SUPPLIES		600	
F. TRAVEL 1. Domestic (Including Canada) Field Trips - Airfare		1,215	
2. Foreign Per Diem (30 man days)			
G. PUBLICATION COSTS		850	
H. COMPUTER COSTS IF CHARGED AS DIRECT COST			
I. OTHER DIRECT COSTS Trailer Mount 600			
Vehicle Rental 600			
Communications 300		1,500	
J. TOTAL DIRECT COSTS (I through I)		32,393	
K. INDIRECT COSTS		11,061	
L. TOTAL COSTS (J plus K)		43,454	
M. AMOUNT OF THIS AWARD (ROUNDED)		\$	
REMARKS: Use extra sheet if necessary			
*Includes anticipated 10% salary increase.			

## GEOELECTRIC SURVEYS

## Task 2.2

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		RESEARCH GRANT BUDGET WORKSHEET	
INSTITUTION AND ADDRESS		NSF PROGRAM	PRINCIPAL INVESTIGATOR(S)
University of Hawaii Honolulu, Hawaii 96822		HAWAII GEOTHERMAL PROJECT	A. S. Furumoto
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT
			\$
A. SALARIES AND WAGES		NSF Funded Man Months (to the nearest tenth)	
1. Senior Personnel		Cal.	Acad.
a. _____ (Co) Principal Investigator(s)			
b. <u>1</u> Faculty Associates		11	
Sub-Total			
2. Other Personnel (Non-Faculty)			
a. _____ Research Associates—Postdoctoral			
b. _____ Non-Faculty Professionals			
c. <u>2</u> Graduate Students			11,760
d. <u>2</u> Pre-Baccalaureate Students (50 wks. ea. @ .10 hr/wk. @ \$2.25/hr.)			2,250
e. _____ Secretarial—Clerical			
f. <u>2</u> Technical, Shop, and Other Field Assts. (30 days. ea. @ \$25/day)			1,500
TOTAL SALARIES AND WAGES			27,390
B. STAFF BENEFITS IF CHARGED AS DIRECT COST			3,005
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)			30,395
D. PERMANENT EQUIPMENT			
E. EXPENDABLE EQUIPMENT AND SUPPLIES			2,000
F. TRAVEL 1. Domestic (Including Canada) 8 inter-island trips - 480; 1 main-land conference; 30 man days per diem for 3			3,680
G. PUBLICATION COSTS			2,000
H. COMPUTER COSTS IF CHARGED AS DIRECT COST 7 hrs @ \$198/hr.			1,386
I. OTHER DIRECT COSTS Communications - 200; M/R Equipment - 1,000; Rental (Drilling) - 2,000; Interisland Freight - 400; Vehicle & Fuel - 2,700; Gas - 460; Diesel - 180.			6,940
J. TOTAL DIRECT COSTS (C through I)			46,401
K. INDIRECT COSTS On Campus (46% of \$25,232) Off Campus (32.49% of \$2,158)			12,308
L. TOTAL COSTS (J plus K)			58,709
M. AMOUNT OF THIS AWARD (ROUNDED)			\$
REMARKS: Use extra sheet if necessary			
*Includes anticipated 10% salary increase.			

THEORETICAL & NUMERICAL  
MODELLING, COMPUTATIONAL GEOPHYSICS,  
MAGNETIC & GRAVITY SURVEYS

Task 2.3

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		RESEARCH GRANT BUDGET WORKSHEET																																					
INSTITUTION AND ADDRESS  University of Hawaii Honolulu, Hawaii 96822		NSF PROGRAM  HAWAII GEOTHERMAL PROJECT	PRINCIPAL INVESTIGATOR(S)  A. S. Furumoto																																				
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT \$																																				
A. SALARIES AND WAGES		NSF Funded Man Months (to the nearest tenth)																																					
1. Senior Personnel		<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <th style="width: 33%;">Cal.</th> <th style="width: 33%;">Acad.</th> <th style="width: 33%;">Summ.</th> </tr> <tr> <td colspan="3" style="padding: 5px;">a. _____ (Co) Principal Investigator(s)</td> </tr> <tr> <td colspan="3" style="padding: 5px;">b. _____ Faculty Associates</td> </tr> <tr> <td colspan="3" style="padding: 5px;">Sub-Total</td> </tr> <tr> <td colspan="3" style="padding: 5px;">2. Other Personnel (Non-Faculty)</td> </tr> <tr> <td colspan="3" style="padding: 5px;">a. <u>1</u> Research Associates—Postdoctoral</td> </tr> <tr> <td colspan="3" style="padding: 5px;">b. _____ Non-Faculty Professionals</td> </tr> <tr> <td colspan="3" style="padding: 5px;">c. _____ Graduate Students</td> </tr> <tr> <td colspan="3" style="padding: 5px;">d. <u>1</u> Pre-Baccalaureate Students 500 hrs., @ 2.75</td> </tr> <tr> <td colspan="3" style="padding: 5px;">e. _____ Secretarial—Clerical</td> </tr> <tr> <td colspan="3" style="padding: 5px;">f. _____ Technical, Shop, and Other</td> </tr> <tr> <td colspan="3" style="padding: 5px;">TOTAL SALARIES AND WAGES</td> </tr> </table>		Cal.	Acad.	Summ.	a. _____ (Co) Principal Investigator(s)			b. _____ Faculty Associates			Sub-Total			2. Other Personnel (Non-Faculty)			a. <u>1</u> Research Associates—Postdoctoral			b. _____ Non-Faculty Professionals			c. _____ Graduate Students			d. <u>1</u> Pre-Baccalaureate Students 500 hrs., @ 2.75			e. _____ Secretarial—Clerical			f. _____ Technical, Shop, and Other			TOTAL SALARIES AND WAGES		
Cal.	Acad.	Summ.																																					
a. _____ (Co) Principal Investigator(s)																																							
b. _____ Faculty Associates																																							
Sub-Total																																							
2. Other Personnel (Non-Faculty)																																							
a. <u>1</u> Research Associates—Postdoctoral																																							
b. _____ Non-Faculty Professionals																																							
c. _____ Graduate Students																																							
d. <u>1</u> Pre-Baccalaureate Students 500 hrs., @ 2.75																																							
e. _____ Secretarial—Clerical																																							
f. _____ Technical, Shop, and Other																																							
TOTAL SALARIES AND WAGES																																							
NSF GRANT BUDGET		\$																																					
B. STAFF BENEFITS IF CHARGED AS DIRECT COST		2,534																																					
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)		16,809																																					
D. PERMANENT EQUIPMENT 3 Tide gauges - 450; Transformers, plastic boxes, heaters, pumps, scales - 600.		1,050																																					
E. EXPENDABLE EQUIPMENT AND SUPPLIES (Recording paper, model study supplies)		1,500																																					
F. TRAVEL 1. Domestic (Including Canada) 10 Interisland trips & 1 mainland		1,950																																					
2. Foreign IUGG Meeting, Grenoble, France - 1975		1,700																																					
G. PUBLICATION COSTS		850																																					
H. COMPUTER COSTS IF CHARGED AS DIRECT COST		2,000																																					
I. OTHER DIRECT COSTS Vehicle Rental 900 Communications 300		1,200																																					
J. TOTAL DIRECT COSTS (C through I)		27,059																																					
K. INDIRECT COSTS		6,566																																					
L. TOTAL COSTS (J plus K)		33,625																																					
M. AMOUNT OF THIS AWARD (ROUNDED)		\$																																					
REMARKS: Use extra sheet if necessary																																							



## TEMPERATURE SURVEY

## Task 2.4

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		RESEARCH GRANT BUDGET WORKSHEET	
INSTITUTION AND ADDRESS  University of Hawaii Honolulu, Hawaii 96822		NSF PROGRAM  HAWAII GEOTHERMAL PROJECT	PRINCIPAL INVESTIGATOR(S)  A. S. Furumoto
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT \$
A. SALARIES AND WAGES		NSF Funded Man Months (to the nearest tenth)	
1. Senior Personnel		Cal.	Acad.
a. _____ (Co) Principal Investigator(s)			
b. _____ Faculty Associates			
Sub-Total			
2. Other Personnel (Non-Faculty)			
a. <u>1</u> Research Associates—Postdoctoral		12	
b. _____ Non-Faculty Professionals			
c. <u>2</u> Graduate Students <u>1</u> @ <u>3</u> mo., <u>1</u> @ <u>8</u> mo., 50% .....			
d. _____ Pre-Baccalaureate Students .....			
e. _____ Secretarial—Clerical .....			
f. _____ Technical, Shop, and Other .....			
TOTAL SALARIES AND WAGES			18,563
B. STAFF BENEFITS IF CHARGED AS DIRECT COST			2,467
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)			21,030
D. PERMANENT EQUIPMENT Slip Rings - 500; Tape Recorder & Digital Inter- face - 2,800; Wire Counter - 100.			3,400
E. EXPENDABLE EQUIPMENT AND SUPPLIES			4,412
F. TRAVEL 1. Domestic (Including Canada) 16 interisland trips - 885; 92 days 2. Foreign per diem - 2,760; 62 days car rental - 1250			4,895
G. PUBLICATION COSTS			500
H. COMPUTER COSTS IF CHARGED AS DIRECT COST 2 hrs @ \$298/hr			596
I. OTHER DIRECT COSTS			
J. TOTAL DIRECT COSTS (C through I)			34,833
K. INDIRECT COSTS On Campus (46% of 16,729) Off Campus (32.49% of 1,834)			8,291
L. TOTAL COSTS (J plus K)			43,124
M. AMOUNT OF THIS AWARD (ROUNDED)			\$
REMARKS: Use extra sheet if necessary			

## SEISMIC STUDIES

## Task 2.5

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		RESEARCH GRANT BUDGET WORKSHEET	
INSTITUTION AND ADDRESS  University of Hawaii Honolulu, Hawaii 96822		NSF PROGRAM  HAWAII GEOTHERMAL PROJECT	PRINCIPAL INVESTIGATOR(S)  A. S. Furumoto
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT
A. SALARIES AND WAGES		NSF Funded Man Months (to the nearest tenth)	
1. Senior Personnel		Cal.	Acad.
a. _____ (Co) Principal Investigator(s)			
b. _____ Faculty Associates			
Sub-Total			
2. Other Personnel (Non-Faculty)			
a. _____ Research Associates—Postdoctoral			
b. _____ Non-Faculty Professionals			
c. <u>2</u> Graduate Students			
d. <u>3</u> Pre-Baccalaureate Students 1200 hrs. @ \$2.75 hr.			
e. _____ Secretarial—Clerical			
f. <u>7</u> Technical, Shop, and Other +16 days @ \$40/day for shipboard salaries			
TOTAL SALARIES AND WAGES			
B. STAFF BENEFITS IF CHARGED AS DIRECT COST			
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)			
D. PERMANENT EQUIPMENT 4 Geophones 1,200			
4 Seismic Amplifiers 1,600			
E. EXPENDABLE EQUIPMENT AND SUPPLIES			
F. TRAVEL 1. Domestic (Including Canada) 12 interisland trips - 1 mainland			
2. Foreign			
G. PUBLICATION COSTS			
H. COMPUTER COSTS IF CHARGED AS DIRECT COST			
I. OTHER DIRECT COSTS Communications 400			
Equipment Maintenance 2,000			
Vehicle Rental (60 Days @ \$30) 1,800			
J. TOTAL DIRECT COSTS (C through I)			
K. INDIRECT COSTS On Campus (46% of 18,904)			
Off Campus (32.49% of 4,480)			
L. TOTAL COSTS (J plus K)			
M. AMOUNT OF THIS AWARD (ROUNDED)			
REMARKS: Use extra sheet if necessary			

## GEOCHEMICAL SURVEY

### Task 2.6

INSTITUTION AND ADDRESS		NSF PROGRAM	PRINCIPAL INVESTIGATOR(S)				
University of Hawaii Honolulu, Hawaii 96822		HAWAII GEOTHERMAL PROJECT	A. S. Furumoto				
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT				
			\$				
<b>A. SALARIES AND WAGES</b> 1. Senior Personnel a. _____ (Co) Principal Investigator(s) b. <u>1</u> Faculty Associates Sub-Total 2. Other Personnel (Non-Faculty) a. _____ Research Associates—Postdoctoral b. _____ Non-Faculty Professionals c. <u>2</u> Graduate Students d. <u>2</u> Pre-Baccalaureate Students e. _____ Secretarial—Clerical f. _____ Technical, Shop, and Other TOTAL SALARIES AND WAGES			NSF Funded Man Months (to the nearest tenth)				
			<table border="1"> <thead> <tr> <th>Cal.</th> <th>Acad.</th> <th>Summ.</th> </tr> </thead> <tbody> <tr> <td></td> <td></td> <td>1.0</td> </tr> </tbody> </table>		Cal.	Acad.	Summ.
Cal.	Acad.	Summ.					
		1.0					
			NSF GRANT BUDGET				
			\$				
			1,727 *				
			1,727 *				
			11,544				
			3,500				
			16,771				
B. STAFF BENEFITS IF CHARGED AS DIRECT COST			687				
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)			17,458				
D. PERMANENT EQUIPMENT			600				
E. EXPENDABLE EQUIPMENT AND SUPPLIES			2,800				
F. TRAVEL 1. Domestic (Including Canada)			5,145				
2. Foreign			1,200				
G. PUBLICATION COSTS			1,000				
H. COMPUTER COSTS IF CHARGED AS DIRECT COST			200				
I. OTHER DIRECT COSTS			600				
J. TOTAL DIRECT COSTS (C through I)			29,003				
K. INDIRECT COSTS			7,715				
L. TOTAL COSTS (J plus K)			36,718				
M. AMOUNT OF THIS AWARD (ROUNDED)			\$				
REMARKS: Use extra sheet if necessary							
*Includes anticipated 10% salary increase.							

## HYDROLOGY

## Task 2.7

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		RESEARCH GRANT BUDGET WORKSHEET	
INSTITUTION AND ADDRESS		NSF PROGRAM	PRINCIPAL INVESTIGATOR(S)
University of Hawaii Honolulu, Hawaii 96822		HAWAII GEOTHERMAL PROJECT	A. S. Furumoto
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT \$
<b>A. SALARIES AND WAGES</b>			<b>NSF Funded Man Months (to the nearest tenth)</b>
<b>1. Senior Personnel</b>			<b>Cal.</b> <b>Acad.</b> <b>Summ.</b>
a. <u>2</u> (Co) Principal Investigator(s)			\$ <u>1,672</u> *
b. _____ Faculty Associates			
Sub-Total			<u>1,672</u> *
<b>2. Other Personnel (Non-Faculty)</b>			
a. _____ Research Associates—Postdoctoral			
b. _____ Non-Faculty Professionals			
c. <u>2</u> Graduate Students			<u>11,120</u>
d. <u>2</u> Pre-Baccalaureate Students			<u>2,000</u>
e. _____ Secretarial—Clerical			
f. _____ Technical, Shop, and Other			
<b>TOTAL SALARIES AND WAGES</b>			<u>14,792</u>
<b>B. STAFF BENEFITS IF CHARGED AS DIRECT COST</b>			<u>661</u>
<b>C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)</b>			<u>15,453</u>
<b>D. PERMANENT EQUIPMENT</b>			<u>1,000</u>
<b>E. EXPENDABLE EQUIPMENT AND SUPPLIES</b>			<u>3,500</u>
<b>F. TRAVEL</b> 1. Domestic (Including Canada)			<u>4,000</u>
2. Foreign			
<b>G. PUBLICATION COSTS</b>			<u>400</u>
<b>H. COMPUTER COSTS IF CHARGED AS DIRECT COST (\$225/hr. X 2 hrs.)</b>			<u>450</u>
<b>I. OTHER DIRECT COSTS</b>			
Consultants            3,000			
Sample Analysis        500			<u>3,500</u>
<b>J. TOTAL DIRECT COSTS (C through I)</b>			<u>28,303</u>
<b>K. INDIRECT COSTS</b>			
(On Campus: 46% - 14,792)			<u>6,804</u>
<b>L. TOTAL COSTS (J plus K)</b>			<u>35,107</u>
<b>M. AMOUNT OF THIS AWARD (ROUNDED)</b>			<u>\$</u>
<b>REMARKS:</b> Use extra sheet if necessary			
*Includes anticipated 10% salary increase.			

## PHYSICAL PROPERTIES OF ROCKS

### Task 2.8

INSTITUTION AND ADDRESS		NSF PROGRAM	PRINCIPAL INVESTIGATOR(S)	
University of Hawaii Honolulu, Hawaii 96822		HAWAII GEOTHERMAL PROJECT	A. S. Furumoto	
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT	
			\$	
A. SALARIES AND WAGES			NSF Funded Man Months (to the nearest tenth)	
			Cal.	Acad.
1. Senior Personnel				
a. (Co) Principal Investigator(s)				
b. 2 Faculty Associates			.50	1.0
Sub-Total				
2. Other Personnel (Non-Faculty)				
a. Research Associates—Postdoctoral				
b. Non-Faculty Professionals				
c. 1 Graduate Students				
d. 2 Pre-Baccalaureate Students				
e. Secretarial—Clerical				
f. Technical, Shop, and Other				
TOTAL SALARIES AND WAGES				
B. STAFF BENEFITS IF CHARGED AS DIRECT COST				
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)				
D. PERMANENT EQUIPMENT Thermal Conductivity Apparatus & Furnace (to be fabricated) - 7,500; Cap. Bridge - 1,850; CONTINUED BELOW **				
E. EXPENDABLE EQUIPMENT AND SUPPLIES				
F. TRAVEL 1. Domestic (Including Canada) (Interisland included)				
2. Foreign				
G. PUBLICATION COSTS				
H. COMPUTER COSTS IF CHARGED AS DIRECT COST				
I. OTHER DIRECT COSTS				
J. TOTAL DIRECT COSTS (C through I)				
K. INDIRECT COSTS				
L. TOTAL COSTS (J plus K)				
M. AMOUNT OF THIS AWARD (ROUNDED)				
REMARKS: Use extra sheet if necessary				
**CONTINUED FROM ABOVE: Digital Voltmeter - 1,400; Decade Resistor Box - 500; Recorder - 1,500; Digital Thermometer - 1,900; Frequency Counter - 700; Oscillator - 1,100.				
*Includes anticipated 10% salary increase.				

**ENGINEERING PROGRAM  
BUDGET SUMMARY**

NATIONAL SCIENCE FOUNDATION  
Washington, D.C. 20550

**RESEARCH GRANT  
BUDGET WORKSHEET**

<b>INSTITUTION AND ADDRESS</b>  University of Hawaii Honolulu, Hawaii 96822	<b>NSF PROGRAM</b>  HAWAII GEOTHERMAL PROJECT	<b>PRINCIPAL INVESTIGATOR(S)</b>  Paul C. Yuen
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<b>PROPOSAL NUMBER</b>	<b>RECOMMENDED DURATION</b>	<b>GRANT NO.</b>	<b>RECOMMENDED GRANT AMOUNT</b>
			\$

A. SALARIES AND WAGES	NSF Funded Man Months (to the nearest tenth)			NSF GRANT BUDGET
	Cal.	Acad.	Summ.	
1. Senior Personnel				
a. <u>1</u> (Co) Principal Investigator(s)			1.0	\$ 2,860*
b. <u>8</u> Faculty Associates		13.6	14.5	57,404*
Sub-Total				60,264*
2. Other Personnel (Non-Faculty)				
a. _____ Research Associates—Postdoctoral				
b. _____ Non-Faculty Professionals				
c. <u>8</u> Graduate Students .....				36,288
d. <u>6</u> Pre-Baccalaureate Students .....				8,500
e. <u>1</u> Secretarial—Clerical .....				8,952
f. <u>1</u> Technical, Shop, and Other .....				5,000
TOTAL SALARIES AND WAGES				119,004
B. STAFF BENEFITS IF CHARGED AS DIRECT COST				8,901
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)				127,905
D. PERMANENT EQUIPMENT				
				14,500
E. EXPENDABLE EQUIPMENT AND SUPPLIES				6,700
F. TRAVEL    1. Domestic (Including Canada)				11,100
2. Foreign				10,000
G. PUBLICATION COSTS				3,700
H. COMPUTER COSTS IF CHARGED AS DIRECT COST				6,000
I. OTHER DIRECT COSTS				
Consultant Fees   \$16,000				
Communications    1,800				
				17,800
J. TOTAL DIRECT COSTS (C through I)				197,705
K. INDIRECT COSTS				
46% of Salaries and wages				54,742
L. TOTAL COSTS (J plus K)				252,447
M. AMOUNT OF THIS AWARD (ROUNDED)				\$

REMARKS: Use extra sheet if necessary

\*Includes anticipated 10% salary increase

**ENGINEERING PROGRAM**  
**Task 3.0**

NATIONAL SCIENCE FOUNDATION  
Washington, D.C. 20550

**RESEARCH GRANT  
BUDGET WORKSHEET**

INSTITUTION AND ADDRESS  University of Hawaii Honolulu, Hawaii 96822	NSF PROGRAM  HAWAII GEOTHERMAL PROJECT	PRINCIPAL INVESTIGATOR(S)  Paul C. Yuen
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PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT \$
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A. SALARIES AND WAGES	NSF Funded Man Months (to the nearest tenth)			NSF GRANT BUDGET
	Cal.	Acad.	Summ.	
1. Senior Personnel				
a. <u>1</u> (Co) Principal Investigator(s)			1.0	\$ 2,860*
b. _____ Faculty Associates				
Sub-Total				2,860*
2. Other Personnel (Non-Faculty)				
a. _____ Research Associates—Postdoctoral				
b. _____ Non-Faculty Professionals				
c. _____ Graduate Students				
d. <u>2</u> Pre-Baccalaureate Students				2,000
e. <u>1</u> Secretarial—Clerical				8,952
f. _____ Technical, Shop, and Other				
TOTAL SALARIES AND WAGES				13,812
B. STAFF BENEFITS IF CHARGED AS DIRECT COST				1,408
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)				15,220
D. PERMANENT EQUIPMENT				
E. EXPENDABLE EQUIPMENT AND SUPPLIES				700
F. TRAVEL 1. Domestic (including Canada)				1,900
2. Foreign				
G. PUBLICATION COSTS				1,000
H. COMPUTER COSTS IF CHARGED AS DIRECT COST				
I. OTHER DIRECT COSTS				
Consultants: Rogers Engineering \$14,000				
John Mink 2,000				
Communications: 600				16,600
J. TOTAL DIRECT COSTS (C through I)				35,420
K. INDIRECT COSTS				
46% of Salaries and Wages				6,354
L. TOTAL COSTS (J plus K)				41,774
M. AMOUNT OF THIS AWARD (ROUNDED)				\$

REMARKS: Use extra sheet if necessary

\*Includes anticipated 10% salary increase

**ENGINEERING PROGRAM**  
**Task 3.1**

NATIONAL SCIENCE FOUNDATION  
Washington, D.C. 20550

**RESEARCH GRANT  
BUDGET WORKSHEET**

<b>INSTITUTION AND ADDRESS</b>  University of Hawaii Honolulu, Hawaii 96822	<b>NSF PROGRAM</b>  HAWAII GEOTHERMAL PROJECT	<b>PRINCIPAL INVESTIGATOR(S)</b>  Paul C. Yuen
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<b>PROPOSAL NUMBER</b>	<b>RECOMMENDED DURATION</b>	<b>GRANT NO.</b>	<b>RECOMMENDED GRANT AMOUNT</b> \$
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A. SALARIES AND WAGES	NSF Funded Man Months (to the nearest tenth)			NSF GRANT BUDGET
	Cal.	Acad.	Summ.	
1. Senior Personnel				
a. _____ (Co) Principal Investigator(s)				\$
b. <u>5</u> Faculty Associates		11.3	8.5	37,535*
Sub-Total				37,535*
2. Other Personnel (Non-Faculty)				
a. _____ Research Associates—Postdoctoral				
b. _____ Non-Faculty Professionals				
c. <u>5</u> Graduate Students .....				22,680
d. _____ Pre-Baccalaureate Students .....				4,500
e. _____ Secretarial—Clerical .....				
f. _____ Technical, Shop, and Other .....				
TOTAL SALARIES AND WAGES				64,715
B. STAFF BENEFITS IF CHARGED AS DIRECT COST				5,508
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)				70,223
D. PERMANENT EQUIPMENT				5,000
E. EXPENDABLE EQUIPMENT AND SUPPLIES				1,000
F. TRAVEL    1. Domestic (Including Canada)				5,400
2. Foreign				6,000
G. PUBLICATION COSTS				1,700
H. COMPUTER COSTS IF CHARGED AS DIRECT COST				3,000
I. OTHER DIRECT COSTS				
Communications				800
J. TOTAL DIRECT COSTS (C through I)				93,123
K. INDIRECT COSTS				
46% of Salaries and wages				29,769
L. TOTAL COSTS (J plus K)				122,892
M. AMOUNT OF THIS AWARD (ROUNDED)				\$

REMARKS: Use extra sheet if necessary

\*Includes anticipated 10% salary increase



## ENGINEERING PROGRAM

Task 3.6

NATIONAL SCIENCE FOUNDATION  
Washington, D.C. 20550RESEARCH GRANT  
BUDGET WORKSHEET

INSTITUTION AND ADDRESS		NSF PROGRAM		PRINCIPAL INVESTIGATOR(S)	
University of Hawaii Honolulu, Hawaii 96822		HAWAII GEOTHERMAL PROJECT		Paul C. Yuen	
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT		
			\$		

A. SALARIES AND WAGES	NSF Funded Man Months (to the nearest tenth)			NSF GRANT BUDGET
	Cal.	Acad.	Summ.	
1. Senior Personnel				
a. (Co) Principal Investigator(s)				\$
b. 3 Faculty Associates		2.3	6.0	19,869*
Sub-Total				19,869*
2. Other Personnel (Non-Faculty)				
a. Research Associates—Postdoctoral				
b. Non-Faculty Professionals				
c. 3 Graduate Students				13,608
d. 2 Pre-Baccalaureate Students				2,000
e. Secretarial—Clerical				
f. 1 Technical, Shop, and Other				5,000
TOTAL SALARIES AND WAGES				40,477
B. STAFF BENEFITS IF CHARGED AS DIRECT COST				1,985
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)				
D. PERMANENT EQUIPMENT				
				9,500
E. EXPENDABLE EQUIPMENT AND SUPPLIES				5,000
F. TRAVEL 1. Domestic (Including Canada)				3,800
2. Foreign				4,000
G. PUBLICATION COSTS				1,000
H. COMPUTER COSTS IF CHARGED AS DIRECT COST				3,000
I. OTHER DIRECT COSTS				
Communications				400
J. TOTAL DIRECT COSTS (C through I)				69,162
K. INDIRECT COSTS				
46% of Salaries and Wages				18,619
L. TOTAL COSTS (J plus K)				87,781
M. AMOUNT OF THIS AWARD (ROUNDED)				\$

REMARKS: Use extra sheet if necessary

\*Includes anticipated 10% salary increase

ENVIRONMENTAL-SOCIOECONOMIC PROGRAM  
BUDGET SUMMARY

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		RESEARCH GRANT BUDGET WORKSHEET																	
INSTITUTION AND ADDRESS  University of Hawaii Honolulu, Hawaii		NSF PROGRAM  HAWAII GEOTHERMAL PROJECT	PRINCIPAL INVESTIGATOR(S)  Robert M. Kamins																
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT																
A. SALARIES AND WAGES		NSF Funded Man Months (to the nearest tenth)																	
1. Senior Personnel		<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <th style="width: 15%;">Col.</th> <th style="width: 15%;">Acad.</th> <th style="width: 15%;">Summ.</th> <th style="width: 55%;"></th> </tr> <tr> <td></td> <td>6</td> <td>2</td> <td>\$ 25,000 *</td> </tr> <tr> <td>1</td> <td></td> <td>8</td> <td>18,926 *</td> </tr> <tr> <td colspan="3"></td> <td>43,926 *</td> </tr> </table>		Col.	Acad.	Summ.			6	2	\$ 25,000 *	1		8	18,926 *				43,926 *
Col.	Acad.	Summ.																	
	6	2	\$ 25,000 *																
1		8	18,926 *																
			43,926 *																
a. <u>2</u> (Co) Principal Investigator(s)																			
b. <u>4</u> Faculty Associates																			
Sub-Total																			
2. Other Personnel (Non-Faculty)																			
a. _____ Research Associates—Postdoctoral																			
b. _____ Non-Faculty Professionals																			
c. <u>4</u> Graduate Students (3 Part-Time).....		10,536																	
d. <u>1</u> Pre-Baccalaureate Students .....		2,000																	
e. <u>1</u> Secretarial—Clerical .....		6,000																	
f. _____ Technical, Shop, and Other .....																			
TOTAL SALARIES AND WAGES		62,462																	
B. STAFF BENEFITS IF CHARGED AS DIRECT COST		6,558																	
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)		69,430																	
D. PERMANENT EQUIPMENT		5,350																	
E. EXPENDABLE EQUIPMENT AND SUPPLIES		600																	
F. TRAVEL 1. Domestic (Including Canada)		5,900																	
2. Foreign																			
G. PUBLICATION COSTS		400																	
H. COMPUTER COSTS IF CHARGED AS DIRECT COST		200																	
I. OTHER DIRECT COSTS																			
Consultants		17,000																	
J. TOTAL DIRECT COSTS (C through I)		98,890																	
K. INDIRECT COSTS		32,873																	
L. TOTAL COSTS (J plus K)		131,763																	
M. AMOUNT OF THIS AWARD (ROUNDED)		\$																	
REMARKS: Use extra sheet if necessary																			
*Includes anticipated 10% salary increase.																			

# PROGRAM ADMINISTRATION AND SUPPORT

## Task 4.0.

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		RESEARCH GRANT BUDGET WORKSHEET	
INSTITUTION AND ADDRESS  University of Hawaii Honolulu, Hawaii 96822		NSF PROGRAM  HAWAII GEOTHERMAL PROJECT	PRINCIPAL INVESTIGATOR(S)  Robert M. Kamins
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT \$
A. SALARIES AND WAGES		NSF Funded Man Months (to the nearest tenth)	
1. Senior Personnel		Cal.	Acad.
a. <u>1</u> (Co) Principal Investigator(s)			3
b. _____ Faculty Associates			1
Sub-Total			\$ 12,500 *
2. Other Personnel (Non-Faculty)			12,500 *
a. _____ Research Associates—Postdoctoral			
b. _____ Non-Faculty Professionals			
c. _____ Graduate Students			
d. _____ Pre-Baccalaureate Students			
e. _____ Secretarial—Clerical			
f. _____ Technical, Shop, and Other			
TOTAL SALARIES AND WAGES			12,500
B. STAFF BENEFITS IF CHARGED AS DIRECT COST			1,534
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)			14,034
D. PERMANENT EQUIPMENT			200
E. EXPENDABLE EQUIPMENT AND SUPPLIES			200
F. TRAVEL 1. Domestic (Including Canada)			400
2. Foreign			
G. PUBLICATION COSTS			100
H. COMPUTER COSTS IF CHARGED AS DIRECT COST			
I. OTHER DIRECT COSTS			
J. TOTAL DIRECT COSTS (C through I)			14,934
K. INDIRECT COSTS			9,890
L. TOTAL COSTS (J plus K)			24,824
M. AMOUNT OF THIS AWARD (ROUNDED)			\$
REMARKS: Use extra sheet if necessary			
* Includes anticipated 10% salary increase.			

## ENVIRONMENTAL

## Task 4.1

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		RESEARCH GRANT BUDGET WORKSHEET	
INSTITUTION AND ADDRESS		NSF PROGRAM	PRINCIPAL INVESTIGATOR(S)
University of Hawaii Honolulu, Hawaii 96822		HAWAII GEOTHERMAL PROJECT	Robert M. Kamins
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT
			\$
A. SALARIES AND WAGES		NSF Funded Man Months (to the nearest tenth)	
1. Senior Personnel		Cal.	Acad.
a. _____ (Co) Principal Investigator(s)			
b. <u>1</u> Faculty Associates		<u>1</u>	<u>4</u>
Sub-Total			
2. Other Personnel (Non-Faculty)			
a. _____ Research Associates—Postdoctoral			
h. _____ Non-Faculty Professionals			
c. <u>3</u> Graduate Students .. (Part-Time) .....			
d. _____ Pre-Baccalaureate Students .....			
e. _____ Secretarial—Clerical .....			
f. _____ Technical, Shop, and Other .....			
TOTAL SALARIES AND WAGES			16,339
B. STAFF BENEFITS IF CHARGED AS DIRECT COST			2,298
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)			18,637
D. PERMANENT EQUIPMENT 3 Sequential Samplers 2940; Reagent Kits 720 3 Hi-Vol. Samplers 1080; Electric Fld. Srce 420			5,160
E. EXPENDABLE EQUIPMENT AND SUPPLIES			300
F. TRAVEL 1. Domestic (Including Canada) 2. Foreign			3,600
G. PUBLICATION COSTS			100
H. COMPUTER COSTS IF CHARGED AS DIRECT COST			
I. OTHER DIRECT COSTS			
Consultants on Environmental Impact Studies			7,000
J. TOTAL DIRECT COSTS (C through I)			34,797
K. INDIRECT COSTS			7,516
L. TOTAL COSTS (J plus K)			42,313
M. AMOUNT OF THIS AWARD (ROUNDED)			\$
REMARKS: Use extra sheet if necessary			
* Includes anticipated 10% salary increase.			

## LEGAL AND REGULATORY

## Task 4.2

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		RESEARCH GRANT BUDGET WORKSHEET	
INSTITUTION AND ADDRESS  University of Hawaii Honolulu, Hawaii 96822		NSF PROGRAM  HAWAII GEOTHERMAL PROJECT	PRINCIPAL INVESTIGATOR(S)  Robert M. Kamins
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT \$
A. SALARIES AND WAGES			NSF Funded Man Months (to the nearest tenth)
1. Senior Personnel			Cal. Acad. Summ.
a. _____ (Co) Principal Investigator(s)			
b. _____ Faculty Associates			
Sub-Total			
2. Other Personnel (Non-Faculty)			
a. _____ Research Associates--Postdoctoral			
b. _____ Non-Faculty Professionals			
c. _____ Graduate Students			
d. _____ Pre-Baccalaureate Students			
e. _____ Secretarial--Clerical			
f. _____ Technical, Shop, and Other			
TOTAL SALARIES AND WAGES			
B. STAFF BENEFITS IF CHARGED AS DIRECT COST			
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)			
D. PERMANENT EQUIPMENT			
E. EXPENDABLE EQUIPMENT AND SUPPLIES			
F. TRAVEL 1. Domestic (Including Canada)			800
2. Foreign			
G. PUBLICATION COSTS			
H. COMPUTER COSTS IF CHARGED AS DIRECT COST			
I. OTHER DIRECT COSTS Consultants			6,000
J. TOTAL DIRECT COSTS (C through I)			6,800
K. INDIRECT COSTS			
L. TOTAL COSTS (J plus K)			6,800
M. AMOUNT OF THIS AWARD (ROUNDED)			\$
REMARKS: Use extra sheet if necessary			

# LAND-USE AND PLANNING

## Task 4.3

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		RESEARCH GRANT BUDGET WORKSHEET	
INSTITUTION AND ADDRESS  University of Hawaii Honolulu, Hawaii 96822		NSF PROGRAM  HAWAII GEOTHERMAL PROJECT	PRINCIPAL INVESTIGATOR(S)  Robert M. Kamins
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT \$
A. SALARIES AND WAGES		NSF Funded Man Months (to the nearest tenth)	
1. Senior Personnel		Cal.	Acad.
a. _____ (Co) Principal Investigator(s)			
b. _____ Faculty Associates			
Sub-Total			
2. Other Personnel (Non-Faculty)			
a. _____ Research Associates—Postdoctoral			
b. _____ Non-Faculty Professionals			
c. <u>1</u> Graduate Students			
d. _____ Pre-Baccalaureate Students			
e. _____ Secretarial—Clerical			
f. _____ Technical, Shop, and Other			
TOTAL SALARIES AND WAGES			4,536
B. STAFF BENEFITS IF CHARGED AS DIRECT COST			292
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)			4,828
D. PERMANENT EQUIPMENT			
E. EXPENDABLE EQUIPMENT AND SUPPLIES			
F. TRAVEL 1. Domestic (Including Canada)			500
2. Foreign			
G. PUBLICATION COSTS			
H. COMPUTER COSTS IF CHARGED AS DIRECT COST			
I. OTHER DIRECT COSTS CONSULTANTS			4,000
J. TOTAL DIRECT COSTS (C through I)			9,328
K. INDIRECT COSTS			2,087
L. TOTAL COSTS (J plus K)			11,415
M. AMOUNT OF THIS AWARD (ROUNDED)			\$
REMARKS: Use extra sheet if necessary			

## ECONOMICS

## Task 4.4

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		RESEARCH GRANT BUDGET WORKSHEET	
INSTITUTION AND ADDRESS		NSF PROGRAM	PRINCIPAL INVESTIGATOR(S)
University of Hawaii Honolulu, Hawaii 96822		HAWAII GEOTHERMAL PROJECT	Robert M. Kamins
PROPOSAL NUMBER	RECOMMENDED DURATION	GRANT NO.	RECOMMENDED GRANT AMOUNT
			\$
A. SALARIES AND WAGES		NSF Funded Man Months (to the nearest tenth)	
1. Senior Personnel		Cal.	Acnd.
a. <u>1</u> (Co) Principal Investigator(s)			1
b. <u>3</u> Faculty Associates			4
Sub-Total			
2. Other Personnel (Non-Faculty)			
a. _____ Research Associates—Postdoctoral			
b. _____ Non-Faculty Professionals			
c. _____ Graduate Students			
d. <u>1</u> Pre-Baccalaureate Students			
e. <u>1</u> Secretarial—Clerical			
f. _____ Technical, Shop, and Other			
TOTAL SALARIES AND WAGES			
B. STAFF BENEFITS IF CHARGED AS DIRECT COST			
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)			
D. PERMANENT EQUIPMENT			
E. EXPENDABLE EQUIPMENT AND SUPPLIES			
F. TRAVEL 1. Domestic (Including Canada)			
2. Foreign			
G. PUBLICATION COSTS			
H. COMPUTER COSTS IF CHARGED AS DIRECT COST			
I. OTHER DIRECT COSTS			
J. TOTAL DIRECT COSTS (C through I)			
K. INDIRECT COSTS			
L. TOTAL COSTS (J plus K)			
M. AMOUNT OF THIS AWARD (ROUNDED)			\$
REMARKS: Use extra sheet if necessary			
* Includes anticipated 10% salary increase.			

## Exploratory Research Drilling Program

Task 5.0 - 1975

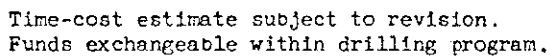
NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		RESEARCH GRANT BUDGET WORKSHEET	
INSTITUTION AND ADDRESS		NSF PROGRAM	PRINCIPAL INVESTIGATOR(S)  AGATIN T. ABBOTT
PROPOSAL NUMBER	RECOMMENDED DURATION 1 C Y	GRANT NO.	RECOMMENDED GRANT AMOUNT \$
A. SALARIES AND WAGES		NSF Funded Man Months (to the nearest tenth)	
1. Senior Personnel		Cal.	Acad.
a. <u>1</u> (Co) Principal Investigator(s)			Summ. 1.0
b. _____ Faculty Associates			
Sub-Total			
2. Other Personnel (Non-Faculty)			
a. _____ Research Associates-Postdoctoral			
b. <u>1</u> Non-Faculty Professionals		9	
c. <u>2</u> Graduate Students			
d. <u>2</u> Pre-Baccalaureate Students			
e. <u>2</u> Secretarial-Clerical			
f. <u>1</u> Technical, Shop, and Other			
TOTAL SALARIES AND WAGES			
B. STAFF BENEFITS IF CHARGED AS DIRECT COST			
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)			
D. PERMANENT EQUIPMENT			
For handling and storage of drill cores & other materials from drill			
E. EXPENDABLE EQUIPMENT AND SUPPLIES			
F. TRAVEL 1. Domestic (Including Canada) (interisland included) Car & jeep rent			
2. Foreign gas & oil included; also per diem			
G. PUBLICATION COSTS			
H. COMPUTER COSTS IF CHARGED AS DIRECT COST			
I. OTHER DIRECT COSTS: Communications \$1,000; Drilling Prog. Managers (10% of costs=\$1,000,000); \$100,000 road construction included (see remarks)			
J. TOTAL DIRECT COSTS (C through I)			
K. INDIRECT COSTS			
On Campus (46% of \$27,800) 12,788			
Off Campus (32.49% of 8,700) 2,826			
L. TOTAL COSTS (J plus K)			
M. AMOUNT OF THIS AWARD (ROUNDED)			
REMARKS: Use extra sheet if necessary			
Rental of field office - \$400/mo \$4,800			
Drilling, Logging, Material \$900,000			
Communications \$1,000			
Prog. Managers fee 100,000			
Road Construction 100,000			
\$1,105,800 total			
(* Includes 10% anticipated salary increase.)			



Hawaii Geothermal Project  
Exploratory Research Drilling  
(For Three-Year Period)  
Total Cost - \$4,054,000

<u>Breakdown</u>	Dollars in Thousands		
	<u>CY75</u>	<u>CY76</u>	<u>CY77</u>
Drilling, logging, coring, etc.	900	1,500	750
Road Construction	100	100	25
Consul. Engineering Co. fee	100	160	78
Personnel	41.4	50	46.5
Office rental	4.8	10.8	3.2
Travel & Per diem	31	31.5	26
Equipment & Supplies	7	8	4
Publication & Computer	4	4	7
Communication	<u>1</u>	<u>1</u>	<u>1</u>
Sub-Total	1,189.2	1,865.3	940.7
Indirect Costs	<u>16.8</u>	<u>24.0</u>	<u>22.3</u>
TOTAL	1,206.0	1,889.3	963.0

The above figures represent drilling costs for the three years of the Exploratory Research Drilling Program. This proposal, however, describes the program for Calendar Year 1975 and, hence, requests only the CY 75 funding of \$1,206,000 for the Drilling Program.



<u>TOTAL</u>	
\$ 2,550,000	-- drilling materials
600,000	-- mobilization
225,000	-- road construction
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\$ 3,375,000	